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Potential Impact of Climate Change on Natural Resources in the Tennessee Valley Authority Region

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REPORT SUMMARY

This report addresses the impacts of changes in climate on water resources, agriculture, forests, outdoor recreation, ecological resources, and air quality in the Tennessee Valley Authority (TVA) region that could be reasonably anticipated to occur over the course of the 21st century assuming a medium greenhouse gas emissions projection. The emphasis is on those effects likely to occur in the next 10 to 40 years, which are likely to be modest—longer range predictions are much more uncertain.

Background

Changes in climate can affect natural resources through a variety of direct and indirect pathways, and rigorous climate change impact assessment therefore encompasses a series of multi-disciplinary analyses that include climate forecasts, physical models, and assessment of adaptive actions. This report builds on estimates in the United Nations Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report, published in 2007. While the IPCC developed forecasts for six scenarios that predict monthly temperature and precipitation across the globe, this project relies on the A1B scenario results, characterized by the IPCC's authors as consistent with a "medium" greenhouse gas emissions projection. This scenario is a business-as-usual case that does not reflect the possible impact of additional efforts to reduce greenhouse gas emissions.

Objectives

- To summarize existing analytic work on climate change impacts as it relates to the TVA region
- To provide preliminary information on climate change impacts that may be useful to TVA in planning future operations
- To identify areas for further research

Approach

The project team conducted an extensive literature review of the potential impacts of changes in climate on water resources, agriculture, forest lands, ecological resources, recreation, and air quality in the TVA region.

Results

Temperatures are forecast to increase roughly 0.8 degrees Celsius from 1990 to 2020 and up to 4.0 degrees Celsius by 2100 in the TVA region based on the A1B scenario. More importantly, precipitation changes could vary substantially, depending on season and location, although projections for precipitation are more uncertain. For example, in the western parts of the region, it is likely that precipitation could increase somewhat in the winter and decrease between 6 and 7

percent in the summer: in the eastern part of the region, it could be wetter, with precipitation increasing between 11 and 13 percent in the winter and remaining unchanged in the summer.

Changes in precipitation are especially important in the TVA region because both its human and natural systems depend critically on the abundance of water resources and uncertainty concerning future water availability will affect virtually every natural resource in the region: hydro- and fossil electric power generation, agriculture, forestry, recreation, ecosystems (particularly potentially endangered species), and some aspects of air quality.

The near-term impacts of changes in climate that might be realized by 2020 are likely to be modest and within the range of existing adaptive capacity, but the impacts will likely become greater by 2050 and in some cases may exceed existing adaptive capacity. One possible exception is in the area of ecological resources, where it is likely that the current endangered status of several species makes them vulnerable to even the relatively modest changes in climate that could manifest by 2020. Drawing conclusions for the end of the century period is very difficult, owing to uncertainties in forecasting climate as well as forecasting the human and natural resource context in which impacts will be experienced.

EPRI Perspective

This literature review represents an important first step in understanding the impact of changes in climate in the TVA region. The results are necessarily limited, however, because in many cases the available literature does not include assessment of climate stressors and receptors specific to the TVA region. Further insights could be gained through more detailed modeling of impacts specific to the TVA region, particularly if that work were focused on detailed modeling of the water resource sector, including estimation of other impacts linked to the water sector.

Keywords

TVA
Climate change
Greenhouse gases
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Ecosystems

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EXECUTIVE SUMMARY

This report summarizes existing research on the physical impacts of climate change on natural resources located in the Tennessee Valley Authority (TVA) region, based on expert review of existing literature.[1] The report is the product of a collaboration among Industrial Economics, Incorporated; the Electric Power Research Institute; and a group of distinguished climate impact assessment experts.

In the TVA region, temperatures are forecast to increase roughly 0.8 degrees Celsius from 1990 to 2020 and up to 4.0 degrees Celsius by 2100 based on the United Nations Intergovernmental Panel on Climate Change (IPCC) estimates for the business-as-usual future scenario. Precipitation changes could vary substantially in the TVA region, depending on season and location, although the forecasts are more uncertain. For example, in the western parts of the region, it is likely that precipitation could increase somewhat in the winter and decrease between 6 and 7 percent in the summer: in the eastern part of the region, it could be wetter, with precipitation increasing between 11 and 13 percent in the winter and remaining unchanged in the summer.

Climate change impact assessment involves consideration of forecasts of future climate, evaluation of the vulnerability of natural and human resources at risk from climate stressors (for example, higher temperatures), and consideration of the capacity of natural and human systems to adapt to climate stressors. Impact assessment excludes the effect of new policy responses taken to reduce greenhouse gas emissions in an effort to mitigate or prevent changes in climate. However, as with assessments conducted by the IPCC, this document focuses on impacts that could occur in the TVA region under a “business as usual” scenario.

The report addresses the impacts of climate change on water resources, agriculture, forests, outdoor recreation, ecological resources, and air quality in the TVA region that could be reasonably anticipated to occur over the course of the 21st century, but with a focus on those effects likely to occur in the next 10 to 40 years. The review has a dual purpose: 1) improving the understanding of existing analytic work on climate change impacts as it relates to the TVA region and 2) providing preliminary information that may be useful to TVA in planning its own operations in the future.

A common factor in virtually all of the key results of this review is the importance of water resources and water availability in the TVA region. In particular, water and uncertainty concerning future water availability are important not just for the major water users in the region

[1] The TVA region is defined as the Authority’s power service area plus other lands within the Tennessee River Basin.

(for example, hydro- and fossil electric power generation), but as a key input to agriculture, forestry, recreation, ecosystems (particularly potentially endangered species), and some aspects of air quality—that is, virtually every other affected natural resource in the region. Water is a critical resource in other regions of the country, but the TVA region may be especially vulnerable to climate change impacts on water availability because both human and natural systems have been established based on the abundance of water resources.

A second common factor in the results of this study is that near-term impacts that might be realized by 2020-2030 are likely to be modest and within the range of existing adaptive capacity and those impacts will likely accelerate by 2050 and in some cases may exceed existing adaptive capacity. One possible exception is in the area of ecological resources, where it is likely that the current endangered status of several species makes them vulnerable to even the relatively modest changes in climate that could manifest by 2020. Drawing conclusions for the end of the century period is very difficult, owing to uncertainties in forecasting climate as well as forecasting the human and natural resource context in which impacts will be experienced.

A detailed review of climate impacts in each of the major natural resource sectors suggests the following conclusions:

1. **Water resources.** In this sector, the most important potential climate stressor is precipitation – if precipitation declines, the region and in particular TVA operations could be significantly affected since currently abundant water resources have created a highly water-dependent regional economy. Substantial impacts could result from localized changes in the temporal distribution of precipitation, with important effects on ecosystem integrity. In addition, a major uncertainty is the future demand for water from agriculture sources. For example, if currently rain fed agriculture requires irrigation, accelerating the already observed trend toward greater irrigation water demand for crops, the impacts of climate change in this sector could be greater.
2. **Agriculture.** Agriculture is a significant and important component of the TVA region's economy. Within the TVA region the overall effects of climate change on agriculture may be modest, but there are likely to be localized occurrences of "winners" and "losers" in the agricultural sector. The greatest uncertainty in estimating climate impacts in this sector relates to the high variation in forecasts of precipitation and water availability. Precipitation effects could be particularly important in the TVA region because the vast majority of crops are currently rain fed.
3. **Forest lands.** Forest lands are also economically important to the TVA region. Climate change is likely to lead to continued increases in forest productivity for the next 10-30 years, with higher temperatures and greater availability of carbon dioxide to support growth. Localized shifts in species distribution are nonetheless possible during this period; and, because significant drying of soils is possible in western parts of the region by 2030, the risks of impacts from climate change increases after 2030. After the mid-century period, more pronounced forest species changes could be seen, which could require adaptive management to facilitate a change from a predominately hardwood to a predominately softwood forest. However, a key uncertainty in these results derives from uncertainty about future precipitation patterns.

4. **Ecological resources.** Literature specific to the TVA region describing impacts of climate change on ecological resources is very limited, but it is clear that the region is currently one of the richest in the nation in terms of biological diversity. In particular, the TVA region provides habitat to an unusually high concentration of threatened and endangered plant, wildlife, and aquatic species. Some of the more subtle changes in forest and aquatic ecosystems that might present modest challenges to commercial forestry and water managers could have more substantial effects to currently threatened or endangered wildlife and plant habitats. The lack of existing studies of these effects makes it difficult to be specific about which regions and species might be most threatened.
5. **Recreation.** Water-based recreation is a major activity in the region, so changes in water availability to support recreation are the key potential climate stressor in this sector as well. To the extent that future demand for biking, hiking, hunting, fishing, and boating opportunities will remain strong in the TVA region, changes in climate can be expected to have substantial impacts in this sector as well.
6. **Air Quality**. The TVA region faces current challenges in maintaining air quality with respect to ozone and particulate matter. Regional haze also affects visibility in the region. Changes in climate can affect each of these pollutants, but in different ways. With temperatures likely to increase, ozone concentrations can be expected to increase in general. Particulate matter concentrations could be affected by soil drying, which would both increase the risk of wildfires and allow dust to become airborne more readily. Increases in wildfires could also lead to increased releases of background mercury to the air. However, air quality is dependent on many meteorological variables and there is significant uncertainty in how those variables might change with climate change. Therefore, it is difficult to make accurate predictions about climate change-induced effects on air quality.

This literature review represents an important first step in understanding the impact of climate change in the TVA region. The results are necessarily limited, however, because in many cases the available literature does not include assessment of climate stressors and receptors specific to the TVA region. Further insights could be gained through more detailed modeling of impacts specific to the TVA region, particularly if that work were focused on detailed modeling of the water resource sector, including estimation of other impacts linked to the water sector.

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INTRODUCTION

1.0 Project Purpose

This report summarizes existing research on the physical impacts of climate change on natural resources located in the Tennessee Valley Authority (TVA) region as shown in Figure 1-1 (comprising the TVA Power Service Area as well as the Tennessee River Basin). The review focuses on the direct effects of reasonably anticipated climate change that will occur between the present and the year 2100; however, given the focus of existing literature and the difficulties inherent in forecasting effects far into the future, the document is more detailed in its coverage of effects that occur between the present and the year 2050. The results of the review should be useful to TVA in two areas: 1) improving the understanding of existing analytic work on climate change impacts as it relates to the TVA region; and 2) providing preliminary information that may be useful to TVA in planning its own operations in the future. The results of the work to date, however, do not reflect any new modeling of climate change or its impacts.

This report was produced through a collaboration of the staff of Industrial Economics, Incorporated (IEc), the Electric Power Research Institute (EPRI), and a group of independent natural resource sector experts who served as Principal Investigators for key components of the study. The remainder of this introductory chapter describes the analytic framework for the literature review and provides a brief summary of the organization and authorship of the document.

1.1 Analytic Framework

1.1.1 Definition of Climate Impact Assessment

This document focuses on climate change impact assessment. Climate change can affect natural resources in many complex ways, through a variety of direct and indirect pathways. Rigorous climate change impact assessment therefore encompasses a series of multi-disciplinary analyses that include climate forecasts, physical models, and assessment of adaptive actions. As illustrated in Figure 1-2, release of greenhouse gases such as carbon dioxide and methane are believed to influence climate and climate variability over time. Climate changes can be forecast by tools such as General Circulation Models (GCMs), which are complex global models used to estimate the impact of changes in greenhouse gases in the atmosphere on future climate outcomes. Although climate modeling is not the main focus of this report, a basic understanding of the output from General Circulation Models is necessary for an understanding of the potential impacts of climate change in the TVA region. Chapter 2 of this document provides a basic review of climate forecasts for the TVA region that are relevant to our impact assessment.

Impact assessment uses the climate forecast results of GCMs as inputs; the scope of impact assessment is illustrated in the center box of Figure 1-2. Impact assessment involves assessing the exposure of a wide range of potentially climate-sensitive receptors to forecast climate changes and then assessing the effects on such measures as soil moisture, crop productivity, forest growth, and species abundance and distribution. The impacts that result from the exposure of climate-sensitive receptors to climate stressors are often further examined to determine if the natural and human systems affected are capable of adapting to these stressors. These "autonomous adaptation" actions in natural systems, for example, might include a plant responding to a lack of water by closing its leaf openings (that is, leaf stomata) to limit evaporation of water contained in the plant. In human systems, for example agricultural fields, autonomous adaptation might also be defined to include such actions as planting drought-resistant cultivars or entirely different crops in response to the same shortage of water. The net result of climate stress and autonomous adaptation is typically defined as the impact of climate change. In this document, the goal is to characterize impacts incorporating the effects of autonomous adaptations, where possible.

As noted in Figure 1-2, impact assessment usually excludes the effect of "planned adaptation," depicted on the right side of the figure. An example of planned adaptation might include the operator of a dam changing operations to ensure enough water is available to irrigate agricultural fields that, without climate change, received sufficient water from rain or that as a result of higher temperatures associated with climate change require additional water to maintain adequate soil moisture at periods of the year important for healthy crop growth. The results presented in this report, except where specifically noted, do not incorporate the effects of planned adaptation. Nonetheless, the impact assessment results presented here may be useful to TVA and others in designing actions to better adapt natural and human systems to climate change.

Impact assessment also excludes the effect of new policy responses taken to reduce greenhouse gas emissions in an effort to mitigate or prevent changes in climate. Policy actions to reduce emissions of greenhouse gases, depicted at the bottom of Figure 1-2, may ultimately be an important component of an overall strategy to respond to the challenges of climate change, but these types of policy responses are not the subjects of impact assessment or of this report.

1.2 Geographic Scope

Geographically, the report focuses on the TVA region, including Tennessee, which comprises more than half of the TVA region, and parts of Kentucky, Virginia, North Carolina, Georgia, Alabama, and Mississippi.

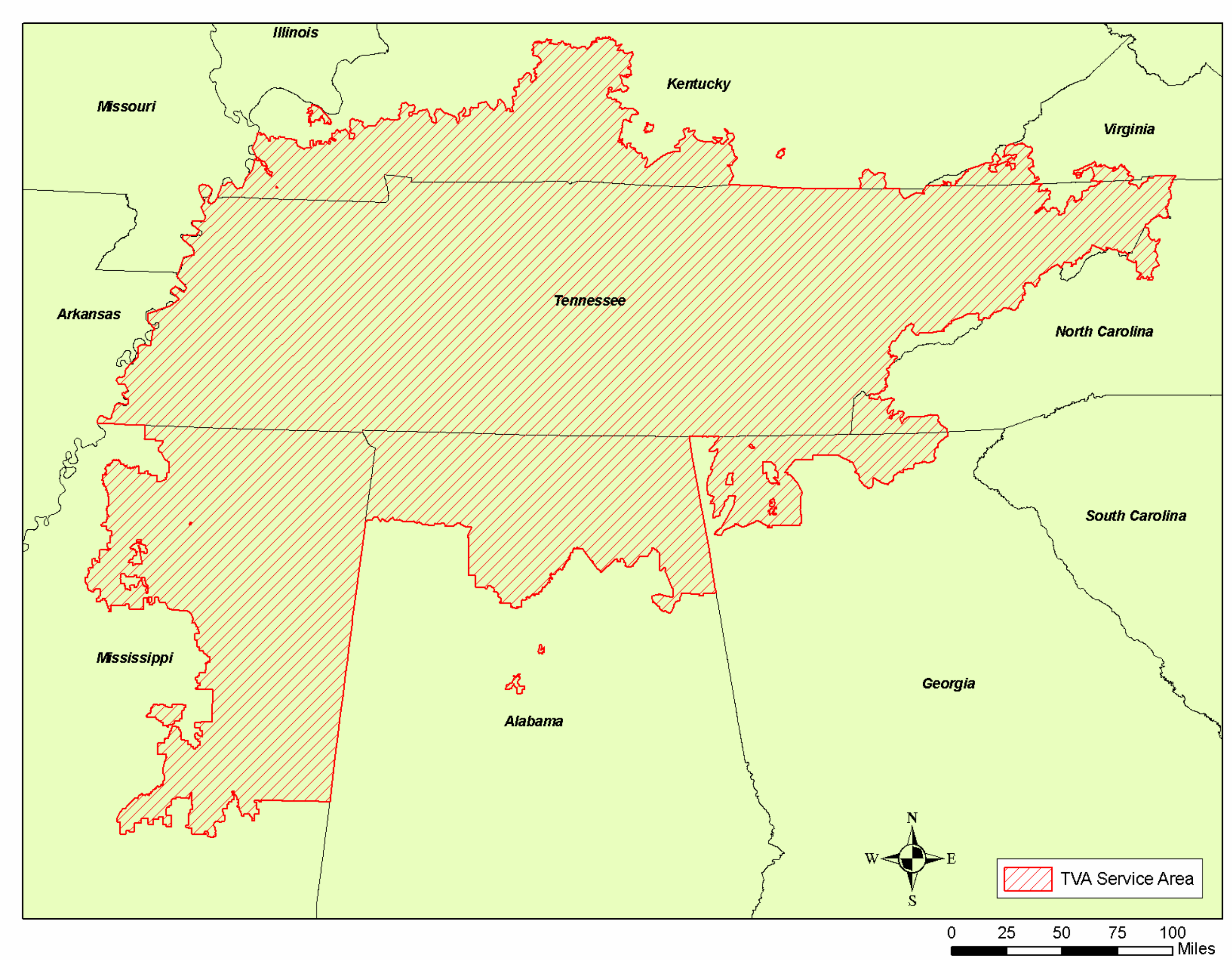

Figure 1-1
TVA region

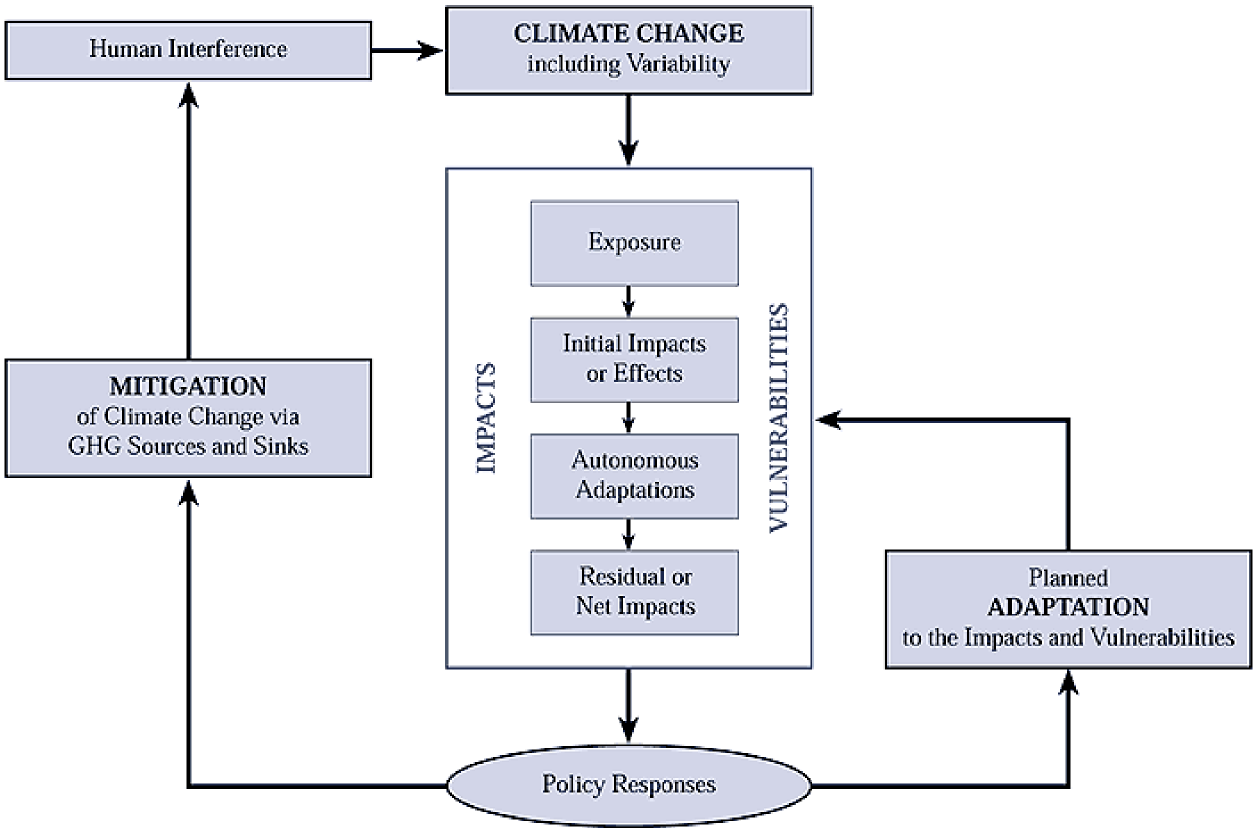

Figure 1-2
Defining the scope of climate impacts

Source: Figure TS-1, IPCC Third Assessment Report, Working Group II (2001).

1.3 Scope of Natural Resources Assessed

The literature review covers six natural resource sectors important in the TVA region:

1. **Water resources.** Abundant water resources characterize the TVA region. Throughout the TVA region, annual mean total rainfall is 52 inches, a figure well above the national average of 30 inches annually (TVA, 2004; EERC, 2009). Eastern Tennessee is one of the wettest regions in the continental United States, receiving nearly double the average annual precipitation observed nationally (EERC, 2009). In part because water is currently abundant in the TVA region, the region is characterized by a wide range of water-dependent economic and recreational activities. TVA itself maintains a system of 49 reservoirs and dams to manage the water levels in the region, balancing the flow requirements for diverse uses such as navigation, flood control, power production and cooling, water supply, water quality, and recreation. Water use for hydroelectric power generation is substantial (approximately 122 billion gallons per day), particularly in the eastern part of the region. Climate impacts in this sector are related to changes in rainfall, but also to changes in temperature, which affects evaporation and evapotranspiration. While water is currently abundant, climate stressors could change that abundance, either locally or region wide, leading to impacts and the need for adaptive measures.

2. **Agriculture.** Agriculture is a major industry in the TVA region, with the values of annual agricultural production (crops and livestock) ranging from $2.6 billion in Tennessee up to $10.3 billion in North Carolina (USDA, 2007). Within Tennessee alone, agriculture is the second largest land use type (42 percent of the land area) (USDA, 2007). Three of the most important agricultural commodities in the region are cattle, broilers, and cotton: other important crops include corn, soybeans, hay, and tobacco (USDA, 2009a, 2009b). Key potential climate impacts in the agricultural sector include changes in total crop yield and changes in livestock production. These physical changes are related to projected changes in temperature, precipitation, and the availability of ambient carbon dioxide. Precipitation effects could be particularly important in the TVA region because the vast majority of crops are currently rain fed, although the percent and quantity of irrigated farmland has been increasing rapidly over the past decade.
3. **Forest lands.** There are approximately 33.1 million acres of forestland and 57.5 billion cubic feet of timber growing stock in the TVA region. Oak/hickory is the dominant forest type in the TVA region, representing approximately 20 percent of the total forestland. Within Tennessee alone, forests cover approximately 55 percent of the total land area and support a $21.7 billion industry employing over 180,000 people. The prevalence of forested areas and the economic importance of forests to the region make this an important sector for assessment of climate impacts. Potential climate impacts in the forest sector include changes in forest composition as well as potential changes in stumpage and harvested volume. Like agriculture, these effects are related to changes in temperature, precipitation, and ambient concentrations of carbon dioxide.
4. **Unmanaged ecosystems.** Extending from the floodplain of the Mississippi River to elevations of over 6,000 feet in the eastern portion of the region, which includes the Great Smoky Mountains, the TVA region supports a wide diversity of terrestrial and aquatic ecological habitats. Terrestrial habitats include riparian forests in the west, and upland oak-hickory and pine-oak forests, high elevation spruce-fir forests, and shrub-dominated or grassy “balds” in the mountains to the east, (CWCS, 2005). Aquatic habitats include warm water systems in the west as well as larger lakes and reservoirs in the eastern and central portions of the region that are deep enough to maintain cold water species such as rainbow and lake trout and cold water streams in the mountainous east. This habitat diversity results in the area being one of the most species-diverse in North America and a center for unusually high levels of endemism. Nonetheless, many plant and wildlife populations in the TVA region are fragmented and at risk from stressors other than climate change; for example, 16 fish species in Tennessee alone are listed by the Federal government as endangered or threatened under the Endangered Species Act, as are 41 species of mussels and 1 crustacean species (FWS, 2009). Potential climate impacts in this sector are related to changes in ecosystem type and acreage and measures of species diversity and are attributed to changes in temperature, precipitation, and carbon dioxide concentrations.
5. **Recreation.** Water resources, managed forests, and unmanaged ecosystems are also an important recreational asset in the TVA region. In addition to its 49 reservoirs, TVA also manages approximately 100 recreation areas within the TVA region (TVA, 2009). In Tennessee alone, there are 54 state parks, 77 state natural areas, and 32 of TVA’s reservoirs (TVA, 2008). Over 25 million people visit these sites annually to participate in biking, hiking, hunting, fishing, and boating activities (TDEC, 2009). The Great Smoky Mountains National Park is also located within the Tennessee Valley. The park offers 2,115 miles of

streams, 700 miles of which are fishable rivers; 800 miles of hiking trails; and other recreational opportunities (NPS, 2009a and 2009b). Natural resource-based recreation is a major activity in the TVA region that could be affected directly by climate changes such as temperature and precipitation changes, as well as indirectly through effects on water resources, forests, and unmanaged ecosystems.

6. **Air Quality.** The TVA region has few metropolitan areas that currently do not meet the National Ambient Air Quality Standards (NAAQS) for ozone, small particulate matter ($PM_{2.5}$), or both. These include the Knoxville and Chattanooga areas for $PM_{2.5}$ and Memphis and Knoxville areas for ozone. The recently tightened ozone standard will likely result in non-attainment status for many other areas. Air pollution is highly sensitive to meteorological conditions, and hence any changes in climate that would affect meteorological conditions, for example, temperature, wind velocities, stagnation events, and humidity, could affect future ozone and $PM_{2.5}$ concentrations. Climate change can also affect air quality by increasing emissions from natural sources and wildfires. Emissions from these sources are also dependent on meteorological conditions.

1.4 Temporal Scope

The temporal scope of this review encompasses effects anticipated to manifest during this century. Within that scope, an attempt has been made to draw concrete conclusions about the degree and extent of impacts for a near-term year (2020) and a mid-century year (2050). Where warranted, attempts were also made to draw conclusions for an end of the century time period (defined loosely as 2070-2100). The ability to make these types of temporally specific statements varies by sector, and uncertainty in projections for the end of century time scale are likely to be affected as much or more by projections of non-climate factors as by climate forecasts. In those sectors where the literature is relatively rich, such as forests and water resources, it was possible to be more definitive about timing: in other areas, in particular unmanaged ecosystems, the relative scarcity of literature specific to the TVA region generally does not support statements about the timing of effects.

1.5 Organization and Authorship of the Document

This report consists of eight chapters:

1. ***Introduction.*** This chapter was developed by the Project Director, James Neumann of Industrial Economics, with assistance from IEc staff. Mr. Neumann is co-editor of *The Impact of Climate Change on the US Economy* (Cambridge University Press, 1999) and is a lead author of Chapter 4: Human Welfare for the EPA Climate Change Science Program, Synthesis and Assessment Product 4.6, *Effects of Climate Change on Human Welfare*. Emily Wasserman of Industrial Economics provided research assistance for this chapter.
2. ***Review of Climate Changes Forecast for the TVA Region.*** The principal author of this chapter is James Neumann, assisted by Brent Boehlert (IEc) and Dr. Kenneth Strzepek, Associate Professor in the Water Resources Engineering program at the University of Colorado at Boulder.

3. ***Water resources.*** Dr. Strzepek is the principal author of this chapter. His research interests include water resource planning and management; river basin planning; and modeling of agricultural, environmental, and water resources systems. He has also conducted numerous assessments of the impacts of climate change on water resources in the United States and internationally. Brent Boehlert provided Dr. Strzepek with technical assistance in the completion of this chapter.
4. ***Agriculture***. The principal author of this chapter is Dr. Richard Adams, Professor of Agricultural and Resource Economics at Oregon State University. Dr. Adams is well-known for his work on the implications of climate change for agriculture and water resources and the tradeoffs between agricultural activity and environmental quality. Brent Boehlert provided Dr. Adams with technical assistance in the completion of this chapter.
5. ***Forest lands***. Dr. Brent Sohngen, Professor in the Department of Agricultural, Environmental, and Development Economics at the Ohio State University, is principal author of this chapter. Dr. Sohngen's work focuses on the relationships among forests, economics, and global climate change, with a particular focus on linking forest ecological and economic models. Malcolm Itter (IEc) provided Dr. Sohngen with technical assistance in the completion of this chapter
6. ***Unmanaged ecosystems***. The principal author of this chapter is Dr. Hector Galbraith, Director of Manomet Center for Conservation Sciences' Climate Change Initiative. Among his other work, he is a lead author of Chapter 4: Human Welfare for the EPA Climate Change Science Program, Synthesis and Assessment Product 4.6, *Effects of Climate Change on Human Welfare*, in which he was responsible for characterizing the effect of climate on ecosystems and ecosystem services.
7. ***Recreation.*** This chapter was authored by Brent Boehlert and Emily Wasserman (IEc), with guidance from Dr. Adams.
8. ***Air quality.*** The principal author of this chapter is Dr. Naresh Kumar, Senior Program Manager at EPRI. He directs research activities related to modeling and monitoring of ozone, particulate matter, atmospheric deposition, regional haze, and interactions between air quality and global climate change.
9. ***Synthesis and conclusions***. This chapter was authored by Project Director James Neumann.

To enable use of this document as a reference for TVA, Chapters 3 through 8 follow a common organizational structure comprising three main sections: 1) a description of the nature of the natural resource at risk from climate change, both generally and in the TVA region; 2) a summary of relevant literature, starting with national studies and progressing where possible to studies of the southeastern region and TVA region; and 3) a discussion of results and suggestions for research areas that might warrant more detailed study.

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2
REVIEW OF CLIMATE CHANGES FORECAST FOR THE TVA REGION

2.0 Introduction

This chapter provides a summary of estimates of future climate changes for the TVA region. The review focuses on the most recent and most widely cited source for these estimates, the United Nations Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report, published in 2007. The chapter begins with a brief description of the approach used by IPCC to develop their estimates, follows with a summary of these results as they apply to the TVA region, and concludes with estimates of temperature, precipitation, and carbon dioxide concentrations mapped to the target years of the report's analyses (2020, 2050, and the late century 2070-2100 period).

2.1 Brief Description of IPCC Climate Change Estimates

As outlined in Figure 1-2 in the previous chapter, assessment of the impact of climate change on natural and human resources requires a forecast of how climate could change in the coming decades. When conducting impact assessments most analysts rely on the climate forecasts generated by the IPCC. Many scientific groups throughout the globe have developed their own General Circulation Models to estimate future climate changes from projections of greenhouse gas emissions. Rather than develop a new climate model, the IPCC has developed a standardized approach for emissions scenarios and other modeling inputs to be used by each of these groups, as well as a standardized set of outputs from the models. The result is a set of climate forecasts for each of six scenarios with outputs through the 21st century for monthly temperature and precipitation across the globe. For the scenario analyzed in this report, A1B, there are 22 such model runs. Each of these six scenarios represents one version of a "business as usual" emissions path for the 21st century; that is, none of the scenarios reflect the impact of additional efforts to reduce greenhouse gas emissions that might be undertaken in the future. From among the IPCC's suite of scenarios, this report relies on the A1B scenario results, characterized by the IPCC's authors as consistent with a "medium" greenhouse gas emissions projection.

The enormous amounts of data produced by these modeling groups can be distilled to provide estimates for specific geographic areas and specific future years from one or multiple model results, but because of the amount of data involved the distillation process can be time-consuming. The spatial resolution of these results varies by model, but in general the models produce results in grids of about two to three degrees of latitude and longitude on a side, or roughly 200 to 300 kilometers square. The TVA region is therefore encompassed within approximately four to six GCM gridboxes, though the actual overlay of modeling gridboxes on the region will vary by model. The scope of this project did not include analysis of the data at the gridbox level; instead, we provide a short summary of readily available results that pertain to the TVA region.

2.2 Summary of IPCC Results Relevant to the TVA Region

The most commonly quoted results from the IPCC report are global multi-model averages or "ensemble mean" results for the end of the 21st century; when ranges are reported they are usually based on the low and high estimates from among the suite of model runs available for each scenario. Results for large geographic regions are also readily available from the IPCC reports, but unfortunately the TVA region is not wholly encompassed by any one of the IPCC sub-continental scale regions. Instead, the TVA region is on the border of the much larger Central North America and Eastern North America regions. Given the climatic variability within the Tennessee Valley region, it may be appropriate in some cases to use climatic projections for both regions combined while in other situations one regional projection may provide a better prediction. We report these results in the remainder of this section.

2.2.1 Temperature

Average U.S. annual temperatures have increased nearly 0.5 degree Celsius in the last 100 years (Hansen et al., 2001), and General Circulation Model results presented in the 2007 IPCC report indicate that annual mean temperatures in the U.S. are likely to rise by roughly two to three degrees Celsius over the next 100 years (Meehl et al., 2007). Temperatures in the TVA region are forecast to increase roughly 0.8 degrees Celsius from 1990 to 2020 and up to 4.0 degrees Celsius by 2100 under the A1B scenario. Figure 2-1 shows IPCC's (2007a) projected mean, winter, and summer temperature changes for North America through 2099 under the A1B scenario.

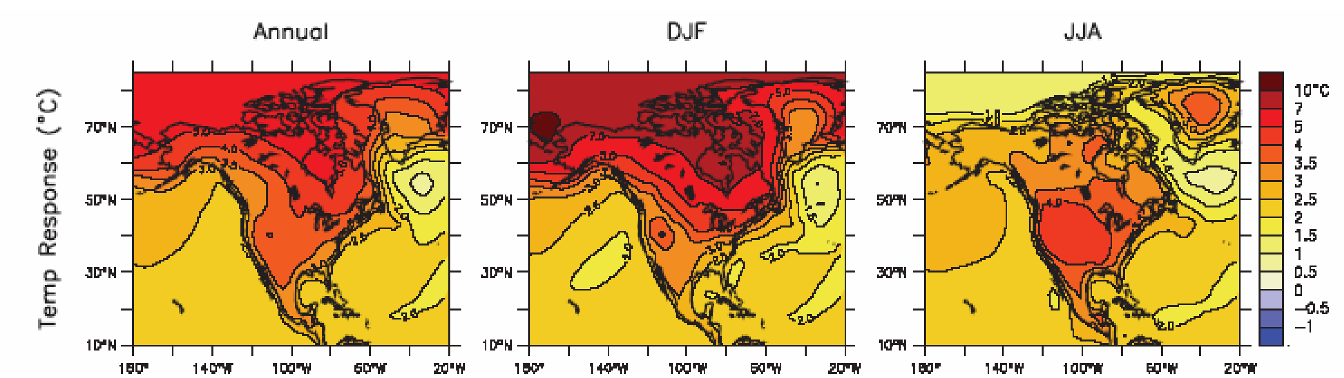

Figure 2-1
Projected mean, winter (DJF), and summer (JJA) changes in temperature between 1980-1999 and 2080-2099 under the A1B scenario

<u>Source</u>: IPCC (2007a)

2.2.2 Precipitation

Climate change has altered the timing, frequency, and magnitude of precipitation events (IPCC 2008; CCSP 3.3, 2008). Overall, precipitation has increased in the U.S. by five to 10 percent over the last 100 years (IPCC, 2001), an upward national trend that will continue as temperatures increase (CCSP, 2009). These increases will vary widely by both region and season. Although recent General Circulation Model analyses have generally failed to forecast precipitation trends with confidence, the models have predicted a 20 percent decrease in summer precipitation in the southwest, and an expected increase in winter precipitation in the northeast (IPCC WG1, 2007a). During winter months, snowfall has been observed to increase in many areas of the United States but has generally decreased in the south, where temperatures were already barely sufficient to produce snow (CCSP 3.3, 2008).

As noted above, the TVA region spans two General Circulation Model regions (the Central and Eastern North American regions). In the central region, precipitation is forecast to increase by 2.6 to 3.0 percent by 2050 in the winter. Although summer temperatures are forecast to increase and thus allow the atmosphere to hold more water, precipitation is anticipated to decrease between 6.1 and 7 percent in the summer months. According to climate models, this apparent incongruity happens because precipitation is anticipated to occur in more intense events, with more extended dry periods in-between. This pattern can lead to reduced overall precipitation (IPCC, 2008). In the eastern region, precipitation increases between 11.3 and 13 percent in the winter and does not change in the summer. Figure 2-2 shows IPCC's (2007a) projected mean, winter, and summer changes in precipitation for North America under the A1B scenario through 2099.

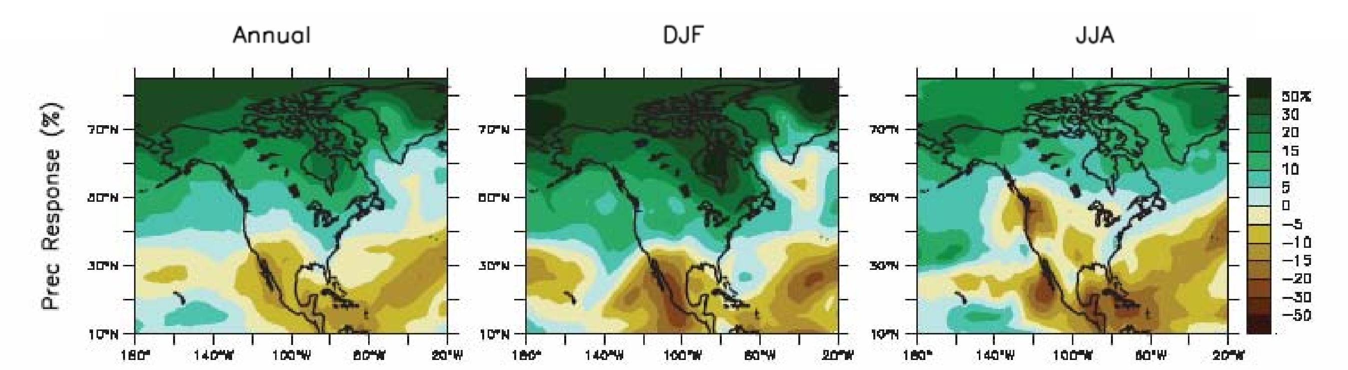

Figure 2-2
Projected mean, winter, and summer changes in precipitation between 1980-1999 and 2080-2099 under the A1B scenario

<u>Source</u>: IPCC (2007a)

Water availability is a function of both precipitation and temperature, a point that will be expanded upon in Chapter 3. It is also important to note that temperature and precipitation are not independent climate variables, but are intimately related. For example, changes in temperature have a pronounced effect on the capacity for the atmosphere to hold moisture: for every one degree Fahrenheit increase in temperature, the atmosphere is capable of holding four percent more water (Hegerl et al., 2007). As a result, most impact assessments use an integrated forecast of temperature and precipitation from individual models, rather than drawing on independent multi-model means.

2.3 Timing of Climate Effects

A great deal of uncertainty remains regarding the response of the climate system to a broad range of natural and anthropogenic influences, making climate forecasts over decadal time scales quite difficult. Nonetheless, it is useful to identify the timing of forecast changes in key climate variables as a guide for this literature review and as a common project-level point of comparison to characterize variation in climate scenarios used in relevant impact assessment literature.

As suggested in Chapter 1, there are three key climate change parameters for the literature review: air temperature, precipitation, and carbon dioxide concentrations. The bullets below review the method used in this study for developing a trajectory for changes in each of these three parameters for the time period through 2100; results are summarized in Table 2-1:

- **Temperature and Precipitation:** The IPCC reports provide a projection of the mean temperature and percentage change in precipitation through the 21st century, including the trajectory of warming and precipitation changes through two near term periods (2011-2030 and 2046-2065) and an estimate for the Central North American and Eastern North American regions by the 2080-2099 period (Meehl et al., 2007 and Christensen et al., 2007). We estimated a global temperature trajectory from 1990 through 2100 and scaled the trajectory for the specific warming and precipitation changes expected in the central and eastern regions through 2100. The IPCC Working Group I Chapter 11 Supplementary Material provides projections for central and eastern North America for two seasons: winter (December-January-February) and summer (June-July-August); we generated our estimates for these same two seasons. As the data in Table 2-1 indicate, both regional projections show a general warming trend, but the eastern region is projected to warm more during the winter months while the central region warms more in the summer months. With respect to precipitation, however, the choice of which regional projection is used could have substantial impacts on future planning. One possible explanation for the significant difference is that the precipitation projections of the central region are dominated by the Great Plains region, which is heavily impacted by the Great Plains Low Level Jet, an airstream affected by land-sea thermal contrasts.
- **Carbon Dioxide Concentration:** IPCC estimates of carbon dioxide concentrations are available from the Third Assessment Report (TAR). As noted in Table 2-1, carbon dioxide concentrations are projected to rise above 700 ppm by the end of the century.

Table 2-1
Climate Projections for 2020, 2050, and End of Century for the TVA region

Key Climate Parameters	Description of Baseline	2020	2050	End of Century (2070-2100)	Source
Air Temperatures	1980-1999 climatic mean temperatures, Central North American Region	+0.8 ° C winter (DJF) +0.9 ° C summer (JJA)	+1.9 ° C winter (DJF) +2.2 ° C summer (JJA)	+3.5 ° C winter (DJF) +4.0 ° C summer (JJA)	IPCC WGI AR4, Chapters 10 and 11 and IEc analysis (see text)
	1980-1999 climatic mean temperatures, Eastern North American Region	+0.9 ° C winter (DJF) +0.8 ° C summer (JJA)	+2.0 ° C winter (DJF) +1.8 ° C summer (JJA)	+3.6 ° C winter (DJF) +3.2 ° C summer (JJA)	IPCC WGI AR4, Chapters 10 and 11 and IEc analysis (see text)
Precipitation	1980-1999 climatic mean precipitation, Central North American Region	+2.6% winter (DJF) -6.1% summer (JJA)	+2.6% winter (DJF) -6.1% summer (JJA)	+3% winter (DJF) -7% summer (JJA)	IPCC WGI AR4, Chapter 11 and IEc analysis (see text)
	1980-1999 climatic mean precipitation, Eastern North American Region	+11.3% winter (DJF) +0% summer (JJA)	+11.7% winter (DJF) +0% summer (JJA)	+13% winter (DJF) +0% summer (JJA)	IPCC WGI AR4, Chapter 11 and IEc analysis (see text)
Carbon Dioxide Concentration	379 ppm in 2005	420 ppm	532 ppm	717 ppm	IPCC II.2.1: CO_2 abundances (ppm) http://www.ipcc.ch/ipccreports/tar/wg1/531.htm using the Bern-CC model
	379 ppm in 2005	418 ppm	522 ppm	703 ppm	IPCC II.2.1: CO_2 abundances (ppm) http://www.ipcc.ch/ipccreports/tar/wg1/531.htm using the ISAM model

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3
POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER RESOURCES

3.0 Introduction

Climate change directly influences the temporal and spatial distribution of water availability through changes in temperature, precipitation, and carbon dioxide (CO_2) concentrations. Collectively, these changes alter runoff patterns, the magnitude and frequency of droughts and floods, water quality, groundwater availability, and other aspects of the water cycle. In response, humans will adapt how they manage water resource systems to minimize any negative effects on economic activities given existing constraints. IPCC and others have reviewed both the effects of climate change and the human response in great detail: rather than replicate this level of detail, the purpose of this literature review is to identify the most important conclusions of the literature and how they may be applicable in the TVA context.

Broadly, the literature has concluded that in response to climate change, temperatures will increase in both the Eastern and Central North American areas (that is, the areas containing the TVA region) and that precipitation will generally decline in the Central region but increase in the Eastern region. There is wide uncertainty in these results, and some climate models show the opposite effects (that is, temperature decreases and precipitation increases). How these anticipated changes will affect the timing and magnitude of annual runoff and ultimately the supply of water in the TVA region is uncertain. Thus, for water resources the only way to determine the net effect of these sets of changes is through the use of hydrologic models. The need for such models in itself is an important conclusion and will require additional study to address.

Note that this chapter reviews the anticipated effects on some of the key water management priorities in the TVA region, including water-based recreation and irrigation. For further discussion of impacts on these two activities, we direct the reader to Chapters 4 (agriculture) and 7 (recreation).

3.1 Characterization of and Trends in Tennessee Valley Water Resources

Water resources are abundant in the TVA region. In Tennessee alone, there are over 60,000 miles of streams, approximately 536,000 acres of lakes, and about 787,000 acres of wetlands, as well as significant groundwater resources (TWRP, 2009). Throughout the TVA region, annual mean total rainfall is 52 inches, a figure well above the national average of 30 inches annually (TVA, 2004; EERC, 2009). However, this number can be misleading given the significant temporal and geographic variation in rainfall across the TVA region. Eastern Tennessee is one of the wettest regions in the continental United States, averaging 45 to 60 inches annually: the mountains are the wettest areas of this region, receiving as much as 90 inches annually. On the other hand, parts of northeastern Tennessee and western North Carolina average only 40 inches of annual rain fall (TVA, 2004; EERC, 2009). Analysis of the Climate Moisture Index (CMI; the ratio of rainfall to potential evapotranspiration, or PET) for this region shows very little change in moisture through 2100. The General Circulation Model results analyzed show a range of six percent drier to eight percent wetter. The CMI is a good proxy for the general magnitude of runoff changes for the basin.[2]

TVA maintains a system of 49 reservoirs and dams to manage the water levels in the region, balancing the flow requirements for diverse uses such as navigation, flood control, power production and cooling, water supply, water quality, and recreation. Water use can also be designated instream or offstream. Instream water uses do not divert water from the stream and include hydroelectric power generation (the largest daily water user), recreation, and aquatic habitat use. In contrast, offstream water use draws water from the source (rivers, reservoirs, aquifers, etc). According to the U.S. Geologic Survey (USGS), approximately 12 billion gallons of water are withdrawn from the TVA river system for offstream use daily, although 95 percent of this water is returned to the surface or groundwater system for reuse (that is, only five percent of withdrawals are used consumptively; TVA, 2004). In Tennessee (which covers the majority of the TVA region), roughly 83.5 percent of water is withdrawn for thermoelectric cooling, 7.8 percent for industrial uses, 8.2 percent for public supply, 0.3 percent for domestic uses (defined in this context as self supplied withdrawals, typically from a well), and only 0.2 percent for irrigation (USGS, 2004). Water use varies substantially within the region; for example, Eastern Tennessee, which uses a substantial amount of water for power generation, is the largest user of water, consuming over twice as much water as Central Tennessee and 24 times as much as Western Tennessee. If power generation is excluded, the eastern portion of the state only consumes three times as much water as Western Tennessee (EERC, 2009).

For the TVA region, Figures 3-1 and 3-2 show the combined public supply, industrial, and irrigation withdrawals in 2000 from surface water and groundwater sources, respectively (from USGS, 2000). The highest surface water withdrawals are in central and eastern Tennessee, northwestern Georgia, northern North Carolina, and northern Alabama. On the other hand, select counties in western Tennessee, Mississippi, and Alabama have the highest groundwater withdrawals, which are generally much lower than withdrawals for surface water.

[2] The CMI results reported here for the TVA region reflect work in progress by the chapter authors, conducted at a one-half degree by one-half degree latitude/longitude resolution. That work is supported by separate World Bank funding and is not yet fully citable, but is part of the Economics of Adaptation to Climate Change initiative (EACC), which is described more fully at www.worldbank.org/environment/eacc.

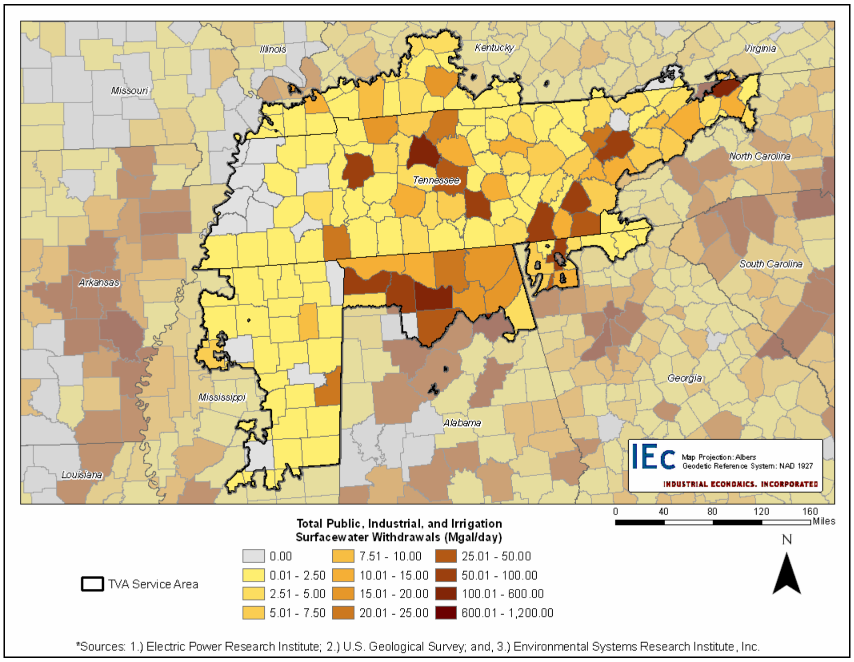

Figure 3-1
Total surface water withdrawals in TVA region counties for public supply, industrial use, and irrigation

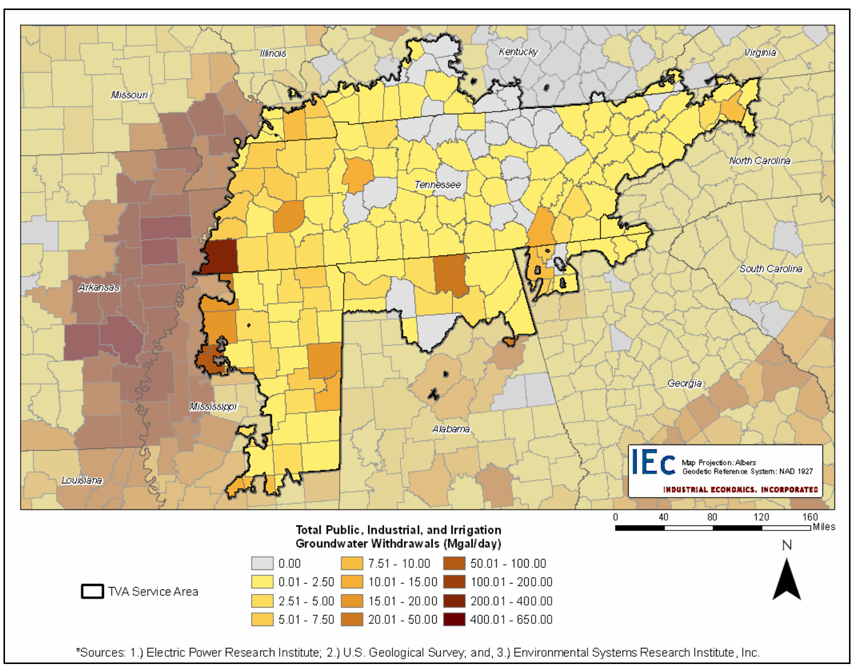

Figure 3-2
Total groundwater withdrawals in TVA region counties for public supply, industrial use, and irrigation

Both recreation and navigation activities depend on instream flows in the TVA region. Navigation represents an important industry for TVA as an average of 54 million tons of freight moves annually along the Tennessee River through TVA's nine lock system (TVA, 2009a and 2009b). Recreation also represents an important instream water user. In a survey conducted by TVA in 2002, as part of workshops evaluating the operations of the Tennessee River system, 34 percent of participants said recreation should be TVA's top priority: other common responses included protecting the natural environment (21 percent), flood control (21 percent), and electricity production (11 percent) (TVA, 2002).

The TVA region is not immune to water-related issues. Changes in local precipitation patterns can therefore have major impacts on both water supply and power supply along with recreation in specific parts of the TVA region even if the region as a whole does not experience a major impact. Change in extreme events, droughts, and daily and weekly flooding pose threats to the TVA region's infrastructure even when monthly and annual water supply does not change dramatically. Additional water-related potential impacts include erosion, contamination from agriculture and surface mining operations, and shifting population patterns (USGS, 2005).

3.2 Literature Review

This section summarizes recent research on the potential effects of climate change on water resources in the United States, with the purpose of evaluating how those resources will be affected in the TVA region. Because there are few studies focused specifically on all or part of the TVA region, we use our judgment to highlight the literature most applicable to TVA, summarize the conclusions of this literature, and suggest how they may be transferrable to the TVA context.

The literature provides several broad conclusions about the effects of climate change on U.S. water resources (from CCSP, 2009; Frederick and Gleick, 1999):

- Climate change has affected and will continue to affect the timing, location, and magnitude of water availability.
- Floods and droughts will become more frequent and more intense.
- Spring and summer snow runoff will shift to earlier in the season as higher temperatures cause snowpack to melt earlier.
- Climate change will alter water quality and groundwater availability.
- Climate change will stress already burdened water systems.
- Better climate change forecasts, particularly at higher spatial resolution, are needed to improve assessments of climate change on water resources (also, Miller et al., 2006).

Several recent documents have focused on how climate change affects water resources, including three IPCC reports (2001, 2007, and 2008), two U.S. Climate Change Science Program (CCSP) reports (2008 and a draft 2009 document), and a report by the Pew Center on Global Climate Change (Frederick and Gleick, 1999). These are discussed and incorporated into this review where appropriate. Although a great deal has been written on the economic consequences of changes in the management of water resources due to climate change, a detailed discussion of this topic is beyond the scope of this chapter. The interested reader can find more information on this topic in the synthesis documents referenced above.

3.2.1 Physical Effects of Climate Change on Water Resources

Climate change affects the water cycle through changes in temperature, the timing and magnitude of precipitation, soil moisture, runoff, the magnitude and frequency of extreme events, and a number of secondary effects (for example, on water quality and groundwater availability). The full range of these effects on water resources is reviewed in the several documents produced by the IPCC in 2001, 2007, and 2008. Here, we provide an overview of runoff, extreme events, and secondary effects, targeting studies that are most applicable to the TVA region. Temperature and precipitation effects are discussed in the previous chapter.

As noted by Miller et al. (2006) and Frederick and Gleick (1999), the models that forecast climate-induced effects face several challenges, including: (1) significant and still poorly-understood differences in temperature, evapotranspiration, precipitation, and runoff outcomes using different modeling approaches; (2) issues with large model bias, which need to be addressed with further research; and (3) insufficient spatial resolution to address effects in more localized regions. It is important to consider these challenges when interpreting results reported in the literature, and to recognize the uncertainty of the results themselves. In the face of this uncertainty, Yohe et al. (1999) suggest that detailed climate research will be most valuable in those areas that the broader studies find are most vulnerable to climate change effects.

3.2.1.1 Runoff

Runoff is dependent on precipitation, temperature, wind speed, humidity, sun intensity, vegetation, and soil moisture (CCSP, 2009).[3] Increased precipitation resulting from climate change does not necessarily mean more water will be available as runoff because increasing temperatures increase evaporation rates, which may result in less available water in many regions (Field et al., 2007; Frederick and Gleick, 1999). Research has suggested that a four degree Celsius temperature increase would require at least a ten percent increase in precipitation to balance evaporative losses (Gleick, 2000). In many regions, projected increases in evaporation exceed increases in precipitation (IPCC, 1998; Gleick, 2000). Changes in the distributions of tree species caused by climate change will affect runoff through changes in forest canopy and species type (affecting evapotranspiration), and the tree root structure (affecting infiltration rate); however, this effect is unlikely to be significant in the time span of this analysis and existing climate models hold vegetation constant through 2100 (IPCC, 2008).

[3] As defined by the U.S. Geological Survey (USGS, 2009): "Runoff is that part of the precipitation, snow melt, or irrigation water that appears in uncontrolled surface streams, rivers, drains or sewers. Runoff may be classified according to speed of appearance after rainfall or melting snow as direct runoff or base runoff, and according to source as surface runoff, storm interflow, or ground-water runoff".

Both increased precipitation and increased runoff have occurred over the past 100 years in the Midwest and Northeast, and increasing streamflows have been observed in the East (CCSP 4.3, 2008; Knowles et al., 2006). Changes in storm intensities and shifts in precipitation patterns resulting from climate change can also have significant impacts on runoff. Figure 3-3 shows the projected changes in annual runoff for 2041 to 2060 relative to a 1901 to 1970 baseline based on mid-range emissions scenarios (hatched areas indicate results with higher confidence). Note that although runoff is projected to increase in the northern portion of the TVA region, particularly in the Cumberland River basin, runoff elsewhere in the region is not anticipated to change, although neither finding is put forth with high confidence. These results are based on large scale General Circulation Model based runoff results rather than local hydrologic modeling, so the magnitude of changes must be used with care. However, the results are generally consistent with the more detailed CMI analysis reported above and with work in progress by the authors.

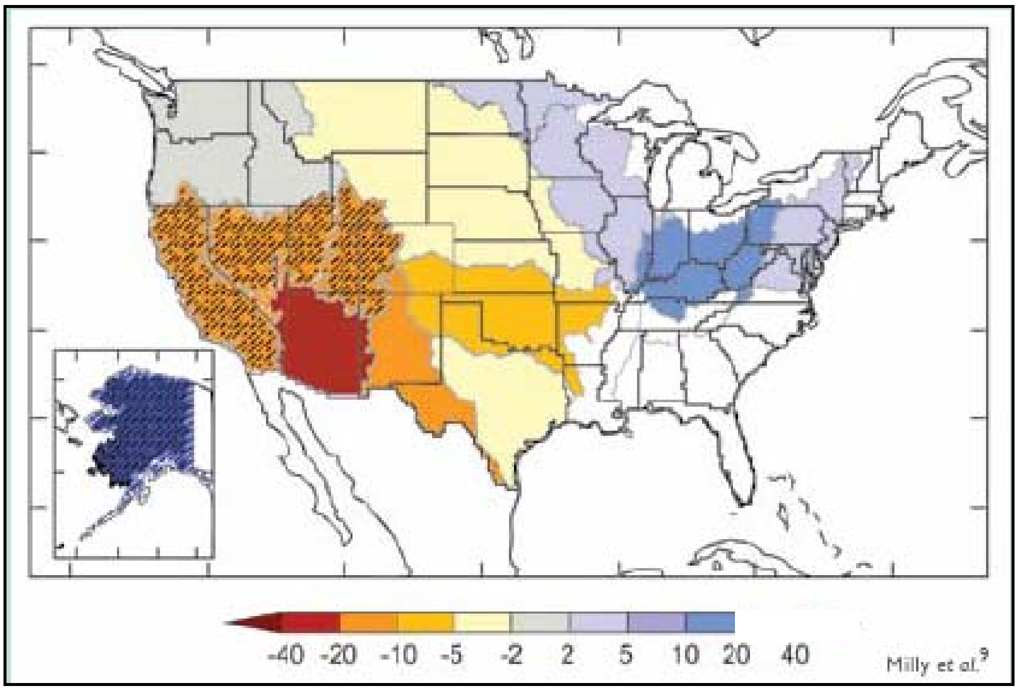

Figure 3-3
Projected percentage changes in annual runoff

<u>Source</u>: Milly et al. (2008), cited in CCSP (2009)

3.2.1.2 Extreme Events

Changing temperature and precipitation patterns will alter the frequency and magnitude of droughts, flooding, and of the El Niño-Southern Oscillation (ENSO). Nationwide, these events have historically resulted in billions of dollars in damage annually (NOAA, 2002).

- **Droughts.** Drought trends in the United States vary widely by location. Depending on how changes in temperature and precipitation interact, droughts may increase or decrease in frequency. For example, from 1900 forward, significant increasing drought trends (using the Palmer Drought Severity Index) have been observed in the Southwest and Rocky Mountain states, whereas the Great Lakes region, Northeast, and certain portions of the South have experienced decreasing drought frequency (Guttman and Quayle, 1996). Figure 3-4 displays drought trends in the U.S. between 1900 and 2008, where hatching indicates statistically significant trends. Observe that drought has generally been decreasing in the TVA region, although this trend is generally not statistically significant across the region.[4]

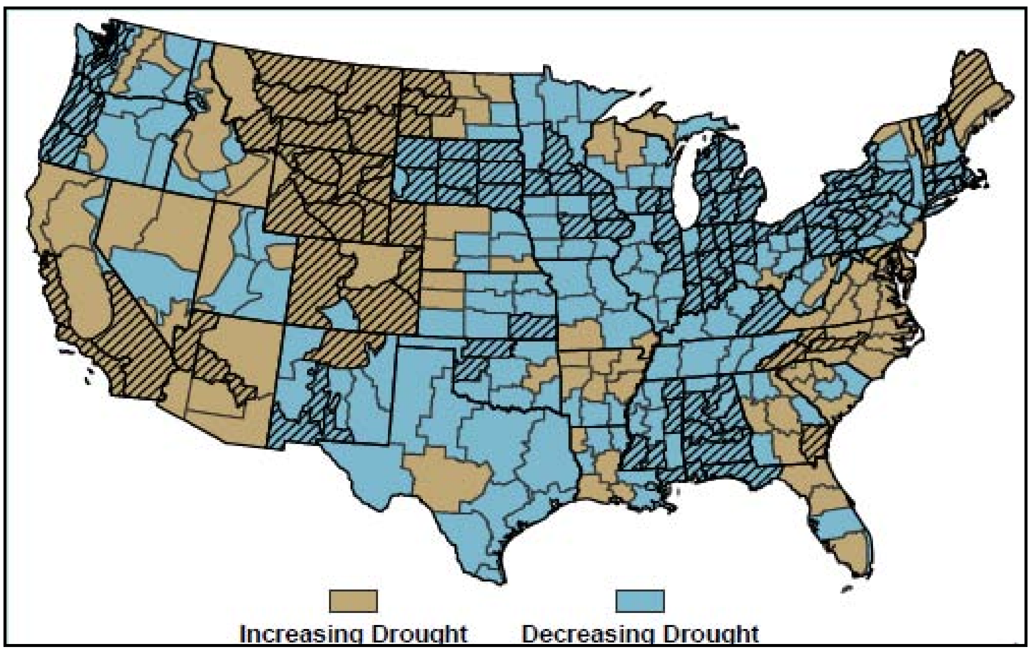

Figure 3-4
1900 to 2008 Drought trends in the U.S.

<u>Source</u>: Guttman and Quayle (1996), updated by and cited in CCSP (2009)

[4] Note that in the TVA region, although 2007 was the driest year on record and 2008 was also an exceptionally dry year, the overall statistical pattern in the region has shown a general reduction in drought.

- **Flooding.** In addition to generally increasing precipitation in the United States, climate change is anticipated to concentrate precipitation more intensely over shorter periods of time. Total precipitation has increased roughly seven percent in the past century, whereas the heaviest rain events have increased by closer to 20 percent (CCSP 3.3, 2008).[5] Consequently, Milly et al. (2002) find that the incidence of great floods in the twentieth century has increased considerably. During future years, the magnitude and frequency of these large-scale rainfall events is anticipated to increase (IPCC, 2008; IPCC WG1, 2007b).
- **El Niño-Southern Oscillation (ENSO) Events**. ENSO is a natural weather phenomenon that occurs as a result of interactions between the ocean and atmosphere over the Pacific Ocean. By changing the thermal profile of the ocean, ENSO events drive climatic events that are associated with both droughts and floods in the United States (Adams and Peck, 2007). The literature has indicated evidence of a strong ENSO signal in the southeastern United States (Adams et al., 1995); and although no consensus exists on the effects of climate change on ENSO magnitude (IPCC WG1, 2007b), the literature has indicated that ENSO frequency may increase (Merryfield, 2006), which may increase the frequency of extreme events in the TVA region.

3.2.1.3 Secondary Effects

The direct physical effects of climate change lead to a number of secondary effects, including changes in water quality, groundwater availability, and soil moisture. Changes in water availability and quality will also affect aquatic and terrestrial ecosystems, although these are not subjects reviewed in this chapter. The interested reader is directed to the ecosystems chapter of this report, as well as Section 4.1 of the latest IPCC report (2008).

Water Quality Impacts

There are relatively few studies that evaluate the impacts of climate change on water quality, as the majority of research efforts have modeled water availability. The available literature suggests increased temperatures may cause longer periods of summer stratification in lakes (CCSP, 2009) and may reduce dissolved oxygen in water bodies while simultaneously increasing the demand for oxygen by increasing respiration rates of organisms (IPCC, 2008). Gooseff et al. (2005) study the implications of climate change on an aquatic ecosystem in the Lower Madison River in Montana and find that resulting higher water temperatures may lead to increased stress on fish populations.

Increases in the intensity of precipitation events, coupled with extended periods of lower streamflow may intensify pollution issues (IPCC WG2, 2007), increasing the number of streams EPA considers to be impaired in future years (EPA, 2008). In particular, prolonged droughts can amplify the warming effects on water of climate change, potentially causing large fish kills or other impacts. As a result of these changes, the biological composition of water bodies may change as species better adapted to warmer conditions outcompete existing species, and

[5] According to the National Climatic Data Center, between 1901 and 2005 changes in precipitation within the TVA region have ranged from zero to greater than 10 percent, with the largest increases occurring in the western portion of the region (EPA, 2009).

alterations in flow regimes may provide additional entry pathways for invasive species (EPA, 2008).

The reference scenario suggests increased summer temperature and no major increase in streamflow. This condition will cause the dissolved oxygen level to decrease in the region, resulting in a reduction in water quality, in particular water's suitability to support oxygen-dependent aquatic organisms. The condition would be worsened if summer flows are reduced.

Impacts to Groundwater

Groundwater systems are anticipated to respond more slowly to changes in climate than surface water systems (IPCC WG2, 2007). Although the impacts of climate change on groundwater systems has not been well studied, generally increasing water use corresponding to increasing temperatures will tax groundwater resources, which provide a significant source of water in many regions of the United States (Alley et al., 1999; Winter et al., 1998). In states containing the TVA region, Tennessee, Alabama, North Carolina, Virginia, and Kentucky each withdraw less than seven percent of their water from groundwater sources; Georgia withdraws 23 percent; and Mississippi withdraws 78 percent (USGS, 2004). Increases in evapotranspiration, changes in vegetation, increases in high runoff events, and other effects of climate change may reduce the potential for infiltration to groundwater systems. The net effect of these changes may be unsustainable levels of groundwater pumping, changes in surface water bodies to which those aquifers are connected, or both.

Soil Moisture

A function of soil type, rainfall patterns, and temperature patterns, soil moisture is a key determinant of crop yields. Soil moisture falls with increasing temperatures due to increased evapotranspiration, but models have shown that increases in precipitation may compensate for these losses. In certain regions of the United States, decreases in precipitation coupled with increases in temperature could have pronounced downward effects on soil moisture (Cao and Woodward, 1998).

3.2.2 The Role of Human Response and Adaptation to Climate Change

Water managers have long been adapting to changing supply of and demand for water resources. In general, these adaptations have been premised on the assumption that past hydrological conditions provide a good guide to future conditions. Climate change challenges this assumption (IPCC, 2008). Milly et al. (2008) observe that water management systems have been constructed on an assumption of "stationarity, the idea that natural systems fluctuate within an unchanging envelope of variability," but that this concept may no longer hold under climate change. This envelope of variability has been based on historical data from stream gauges, lake levels, groundwater levels, agricultural flow meters, and other measurement devices that have provided decades of data. Although water systems are generally resilient to extreme events within the historically observed range (IPCC, 2008), by altering the water cycle, climate change can alter both the average and extreme conditions under which these systems will operate.

In response to climate change and other challenges (see Section 2.4 of this chapter), existing systems will seek to adapt to a new set of conditions. The latest IPCC report (2008) differentiates between *autonomous adaptations* and *planned adaptations*. Autonomous adaptations are unplanned responses to changes in water supply and demand that may lessen the consequences of climate change. For example, farmers may switch to less water-intensive or more resilient crops in response to changes in water availability or drought frequency. Several other examples of autonomous adaptations are described in the agriculture chapter of this report. Planned adaptations, on the other hand, result from deliberate policy decisions that specifically seek to address and minimize the effects of climate change. In the United States, concrete examples of planned adaptations that relate solely to climate change have been rare, as planning decisions have typically considered a broad range of future uncertainties and goals related to water resource management (IPCC, 2008). Nevertheless, adaptive responses to changes in the water cycle can reduce the vulnerability of managed water systems to climate change.

3.2.3 Effects of Climate Change on the Managed Water System

Climate change coupled with human adaptation will influence both the demand for and supply of water. These changes will affect a wide range of components within the water system TVA manages, including hydropower generation, thermoelectric cooling, reservoir-based recreation, municipal and industrial uses, and environmental flows.

3.2.3.1 Electricity Generation

In addition to affecting the demand for electricity (for example, because of increased air conditioning), climate change will directly affect electricity generation by changing runoff and water temperatures. Fossil fuels and nuclear power both depend on cooling water from rivers for their operation, and hydropower relies on instream flows. In Tennessee, fossil fuel and nuclear power collectively generate nearly 88 percent of electricity needs for the state; hydropower accounts for the majority of the remainder (EIA, 2008). The USGS (2004) estimates that water withdrawals for thermoelectric cooling represent roughly 83 percent of total withdrawals in Tennessee. Reductions in water supply or increased water temperatures are therefore likely to disrupt energy production in thermal and nuclear energy plants (IPCC, 2008).

Whether hydropower generation decreases or increases as a result of climate change depends on changes in runoff patterns (net of any losses related to increased reservoir evaporation) along with any resulting changes in management priorities. As documented by Frederick and Gleick (1999), between 1987 and 1991, a drought in California caused hydropower generation to decrease substantially, causing significant increases in power generation from fossil fuel sources. This change to replacement sources cost ratepayers roughly $3 billion and increased greenhouse gas emissions. The few studies conducted on the implications of climate change on hydropower generation conclude that the effects may be either positive or negative, depending on how the timing and magnitude of runoff are affected. Lehner et al. (2005) find that hydropower generation in parts of northern Europe and Russia will increase by 15 to 30 percent by the 2070s, whereas generation in Portugal and Spain will decline by 20 to 50 percent (assuming IS92a emissions). Findings also vary depending on scenario and modeling approach. Using a CGCM1 model projection (two degree Celsius warming) Buttle et al. (2004) find that generation on the Niagara and St. Lawrence Rivers falls by 25 to 35 percent; using the HadCM2 model, these authors find a three percent gain in generation. With minor runoff changes expected for the TVA region, the net effect would be a modest increase in hydropower potential in the region because of higher runoff or potentially a slight decrease because of greater evaporation losses from reservoirs caused by increases in temperature.

3.2.3.2 Agricultural Use

Although presently only two percent of farmland in Tennessee is irrigated, irrigated acreage in Tennessee has been growing rapidly, following the trend in much of the eastern United States. As described in the agriculture section of this document, increasing drought frequency resulting from climate change is likely to accelerate this trend (also see IPCC, 2008). Agricultural water use in the TVA region is likely to increase for two reasons: (1) wider adoption of irrigation in the TVA region since irrigation provides crops a more consistent and continuous supply of water than precipitation and (2) increased biophysical crop water demand due to rising temperatures. Whether sufficient water is available to meet these additional water demands given competing demands for water is uncertain.

Additional information on how climate change is expected to affect agriculture is provided in the agriculture chapter of this report.

3.2.3.3 Municipal and Industrial Uses

IPCC (2008) reports that although a small user relative to irrigation, municipal and industrial users are often prioritized over agricultural users. Although municipal and industrial water demand growth is expected to be primarily attributable to non-climate related factors such as population growth, economic growth, and demographic change (Vorosmarty, 2000; Alcamo et al., 2007), climate change will also affect demand. Rising temperatures are the primary cause for increases in municipal water demand, which will be driven primarily by increased water demand for garden and lawn watering (Arnell, 1998; Water Research Foundation, 2009). The Water Research Foundation reports that industrial water use is primarily associated with cooling needs. Although this use is relatively insensitive to climate change as it is primarily dependent on technological modes of use, increased water temperature may decrease the efficiency of cooling water, necessitating increased water withdrawals. IPCC (2008) notes climate change might indirectly lead to increased industrial cooling water demand as more electricity is needed for cooling purposes.

3.2.3.4 Reservoir-based Recreation

Among recreational activities in the TVA region, water-based activities rank among the highest in terms of participation. As described in the recreation chapter of this document, TVA manages 49 reservoirs across its service area. According to the National Survey of Recreation and the Environment (NSRE, 2007), swimming in lakes or streams or boating each have participation rates of over 37 percent while fishing has a participation rate of over 30 percent in the TVA region. Research has demonstrated that lower reservoir levels and decreased in-stream flows cause decreases in recreational activity (Shaw, 2005) and that these coupled with warmer water temperatures negatively affect fishing activity (Pendleton and Mendelsohn, 2000). As climate change affects water availability and increases water temperatures in the TVA region, recreational resources will be affected. Whether these effects will be positive or negative depends largely on how the timing and magnitude of runoff affects in-stream flows and reservoir levels. If water availability declines, adaptation and reprioritizing of water uses within the TVA region would avoid some negative impacts to recreational activities (for example, by maintaining higher reservoir levels or flows in frequented recreational resources), although many negative impacts due to increasing temperatures may be unavoidable. For example, Ahn et al. (2000) estimate reduction in utility derived from trout fishing of two to 20 percent given an increase in temperatures of one to five degrees Celsius.

For more information on this issue, we direct the reader to the recreation chapter of this report, as well as a recent framework for evaluating climate change by Shaw and Loomis (2008) and a review of climate change-related impacts to recreational resources by the U.S. Climate Change Science Program (CCSP 4.6, 2008).

3.2.3.5 Navigation

Inland navigation is an important use of TVA's water system; 54 million tons of freight are shipped along the Tennessee River annually (TVA 2009a). Navigation is also a particularly vulnerable industry given its dependence on specific water levels. IPCC (2008) reports that droughts, floods, and increased extreme events all can have negative and disruptive effects on inland navigation. Droughts have the potential to reduce stream flows below navigable levels, floods may increase flow to dangerous speeds, and other extreme events can disrupt navigation schedules. Zebisch et al. (2005) note that while extreme summer heat and increased frequency of extreme events will affect inland navigation negatively, particularly on unmanaged rivers. The navigation sector in other regions of the United States may benefit from fewer frost days in the winter, but this is not an issue for the TVA region.

The overall effect of climate change on inland navigation throughout the TVA region will depend on how precipitation and runoff patterns in TVA change and how TVA manages its water resources amongst competing users.

3.2.3.6 In-stream Habitats

Changes to in-stream flow levels may have substantial impacts on the habitats and biodiversity supported by rivers and other water bodies in the TVA region. IPCC (2008) reports that low water levels can cause reproductive problems among fish and amphibian species and that river-spawning fish may also be directly impacted by changes in flow levels. Jones et al. (2006) emphasize the importance of taking a holistic approach to the evaluation of the effects of changes in stream-flow, reviewing the accompanying habitat changes in addition to the direct effects on species dependent on the specific flow pattern.

Within the TVA region, the overall effects of climate change on in-stream flow will vary depending on run-off cycles, precipitation levels, and river characteristics. In-stream flow rates will also be indirectly affected by water management decisions between competing water uses. The ecosystems chapter of this report addresses these issues in greater depth.

3.2.4 Additional Water Management Challenges

Activities that rely on how water is managed in the TVA region will need to adapt to climate change in the presence of a variety of other challenges, including:

- **Conflict over water.** Many areas in the United States, both in the East and West, have experienced conflicts between competing uses of water resources. The Bureau of Reclamation (2005) has identified regions likely to experience future conflict over water in the West, where conflict has generally been more pronounced; however, conflict in the eastern U.S. has become more frequent in recent years. For example, the 2007 water dispute between Georgia and Florida focused on allocating water flows among hydropower, endangered species, Atlanta water supplies, and a downstream mussel fishery during droughts in the Apalachicola-Chattahoochee-Flint River Basin (Feldman et al., 2008). Changes in water availability driven by climate change are likely to exacerbate these conflicts (CCSP, 2009).
- **Aging water supply infrastructure** also poses challenges, as existing infrastructure is likely to require significant monetary investments in future years. In a 2002 report, EPA indicated that funding for drinking water and wastewater infrastructure in the United States would be $500 billion short by 2020 (EPA 2002), assuming expenditures continue at their current rate. Climate change may increase required infrastructure modifications to meet changing hydrological conditions.
- **Increases in regional population** may have significant effects on water demand. The U.S. Census Bureau estimates that the U.S. population will increase from 310 million to 357 million between 2010 and 2025 and rise to 409 million by 2050 (Census, 2008). In Tennessee, populations are anticipated to increase from 6.8 million in 2010 to 7.6 million in 2025 (TACIR, 2003). These changes are likely to place additional burdens on water systems (CCSP, 2009). Note that the effect of increased population may be partly counterbalanced by a generally decreasing per capita water use trend (CCSP 4.3, 2008).
- **Uncertainty over future water use.** Unlike the relationship between climate change and water availability, research has not defined a clear linkage between climate change and water use. Although water use generally rises with increasing temperatures and falls with increasing precipitation, use is driven primarily by non-climate-related factors, creating additional challenges for water resource managers (IPCC, 2008).

3.3 Discussion

Preceding sections of this chapter review 1) the state of water resources in the TVA region and 2) selected literature on the effects of climate change on water resources supply, demand, and related indirect linkages. Although we identified no studies specific to the TVA region, the findings in the large volume of literature reviewed here, specifically those relevant to the Southeastern United States, are sufficiently robust to suggest possible effects of climate change on water resources within the TVA region. We also use findings from this literature to identify areas of research needed to support these qualified conclusions. These areas are discussed in the following sections.

3.3.1 Conclusions of the Literature

Climate change may affect activities within the TVA region that are sensitive to changes in water quality, or the timing and magnitude of water availability.

Hydrologic Resources. Changes in evapotranspiration and precipitation will cause changes in the amount and the distribution, spatially and temporally, of surface runoff. These changes will impact streamflow and groundwater flow and in turn the aquatic ecosystem, where even slight changes in ecological characteristics can greatly impact ecosystem integrity. For the magnitude of the climate change suggested by the reference scenario, only a modest change in runoff is expected.

Water Demands. Water use is divided into market and non-market use. Market uses can be aggregated into four major sectors:

- Agriculture: irrigation and livestock
- Industry: industrial, mining, navigation, recreation
- Energy: thermoelectric cooling and hydroelectric power
- Municipal: public supply, domestic, and commercial.

Non-market water uses are for aesthetic uses, certain recreational uses, and for aquatic ecosystem integrity.

Among market uses, climate change will increase evapotranspiration and therefore will increase agricultural water use. The likely expansions in irrigated agriculture, which consumes more water than rain-fed agriculture, will further increase agricultural water demands. The prospect of increased water use is discussed further in the agricultural chapter of this report. Climate change may also increase evaporative losses from industrial and thermoelectric cooling uses and may increase reservoir losses even in the TVA region. Although other market sectors will not be significantly affected by climate change, certain non-market uses such as aquatic ecosystem integrity may be affected.

Water Quality. To improve water quality, either water management systems can be designed to provide more water for mixing with pollution to avoid violating concentration-based water quality standards or investments can be made in wastewater treatment systems to remove more pollution. Climate change can affect water quality in two ways: (1) reductions in hydrologic resources may leave less dilution flows in the stream, leading to degraded water quality or higher expenditures on wastewater treatment; and (2) in response to climate change, certain water uses such as agriculture may increase the concentration of pollution being released to streams. Together, these possibilities pose a threat to water quality and the integrity of the aquatic ecosystem.

3.3.2 Data and Modeling Gaps

A major challenge in assessing the effects of climate change on water supply (runoff) and water demand such as irrigation within the TVA region is the lack of sufficient spatial resolution of precipitation and temperature changes. There is a growing literature on downscaling, in which techniques are developed to take General Circulation Model forecasts and translate them into climate forecasts with greater resolution (see, for example, Mearns et al., 2001; Adams et al., 2003; Gaffin et al., 2004). Regional or finer scale climate change forecasts are needed to understand not only the effects of climate change on water resources but on other sectors and resources at risk, such as agriculture and forestry.

There is a need for the application of existing hydrologic, hydraulic, and water resource systems models to quantify the impacts of climate change on the TVA systems at a range of temporal and spatial scales.

3.3.3 Recommendations for Future Research

Recommendations for future impacts research include:

- A focused hydrologic analysis under finer resolution of climate forecasts. Specifically, hydrologic systems would be modeled at monthly and daily temporal scales and at catchment spatial scale.
- A focused assessment of extreme events and the resulting impacts on water supply and demand, focusing on: (1) droughts; (2) floods at monthly, daily, and hourly time scales; and (3) modeling how reservoirs and flood control systems can be used to "mitigate" the impacts of extreme events.
- An analysis of how climate change affects:
  - Ecological, market, and non-market water demands
  - Water quality, and in particular, river and reservoir temperatures
  - Net reservoir evaporation

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4
POTENTIAL EFFECTS OF CLIMATE CHANGE ON AGRICULTURE

4.0 Introduction

Through changes in temperature, precipitation, and carbon dioxide (CO_2) concentrations, climate change has biophysical effects on crops and livestock. As humans adapt to these effects, agricultural productivity and the distribution of agricultural commodities will change. The IPCC and others have reviewed these effects in great detail; the purpose of this literature review is not to replicate that level of detail, but rather to identify the most important conclusions of the literature and how they may be applicable to the TVA context.

Broadly, the literature has concluded that climate change associated with mid-range forecasts from General Circulation Models will increase agricultural production to the north of the TVA region and decrease production to the south; however, research has not clearly established how production will be affected within the region. This continuing uncertainty is an important conclusion in itself and will be discussed in further depth below.

4.1 Tennessee Valley Agriculture: Characterization and Trends

Agriculture is a major industry in the TVA region, with values of annual agricultural production (crops and livestock) ranging from $2.6 billion in Tennessee up to $10.3 billion in North Carolina (USDA, 2007a). Figure 4-1 shows the acres in U.S. farms as a percent of county land area in 2002 and Figure 4-2 shows the net cash farm income of operation by county that year. Observe that in the TVA region, although agriculture is most concentrated in southern Kentucky and central and western Tennessee, the highest farm income occurs in northern Alabama and Georgia.

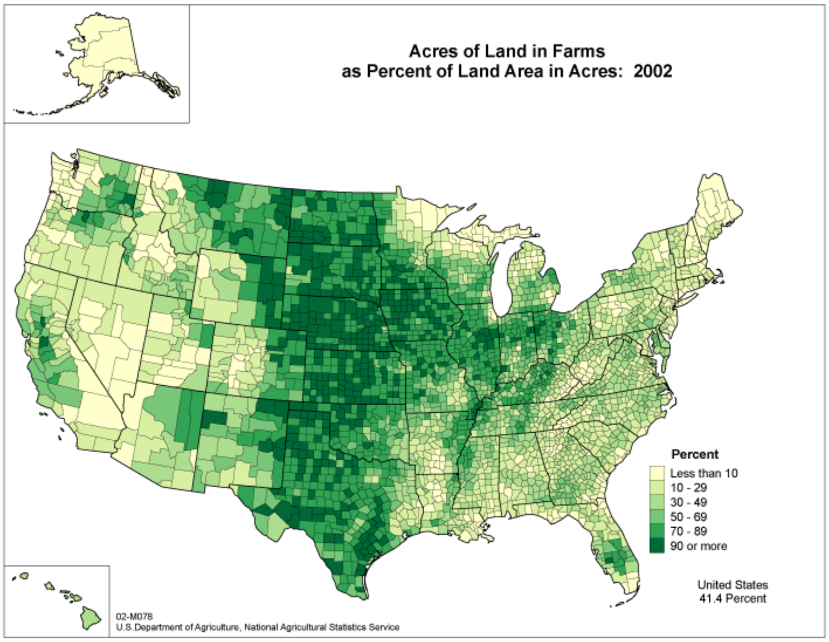

Figure 4-1
Acres in U.S. Farms as percent of county land area, 2002

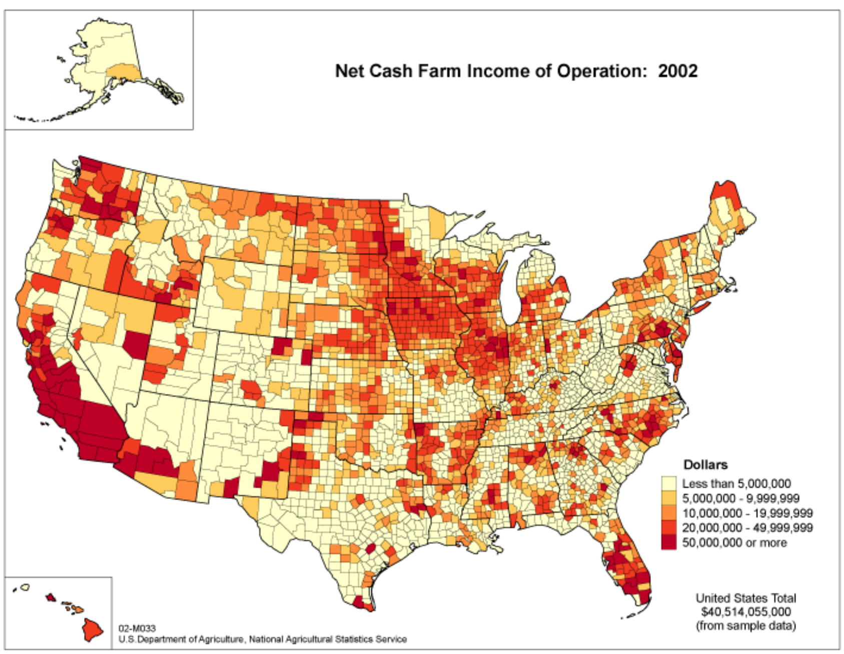

Figure 4-2
Net cash farm income of operation in U.S. counties, 2002

Source: USDA (2002).

While there exists substantial data describing the production of crops in each county of the TVA region, development of a detailed regional characterization was beyond the scope of this effort. We present a characterization of Tennessee agriculture below. While not a complete picture of the TVA region, it provides a useful frame of reference, especially since the majority of TVA's jurisdiction is within Tennessee. We also note, based on a review of agricultural production for each of the seven states, the similarity of crop types across the region.

In Tennessee, agriculture is the second largest land user. The U.S. Geological Survey (USGS) Land Cover Institute's (LCI) land cover area statistics show that approximately 30 percent of Tennessee's land is used for agricultural purposes (calculated as the sum of the fallow, grain, grassland, orchard, pasture, and row crops land cover categories). Forests represent the largest category of land use in Tennessee, covering an additional 61 percent of the state (calculated as the sum of the deciduous forest, evergreen forest, and mixed forest land cover categories). LCI cautions that these values are preliminary, as they are based on raw pixel counts and do not account for potential misclassification of land areas (USGS, 2009). The U.S. Department of Agriculture (USDA) reports that across Tennessee, there are 79,280 farms producing various crops and livestock products. These farms, used for the cultivation of crops and livestock, cover 11 million acres, equal to approximately 42 percent of the state's total land area (USDA, 2007b). This discrepancy suggests that some of the land characterized as forest by LCI may be wooded pastureland or used for some other agricultural purpose.

Irrigation plays a small role in agricultural production in Tennessee. Of the farms in Tennessee, only three percent contain any land that is irrigated. Irrigated land accounts for less than two percent of total farmland in Tennessee (USDA, 2007c). Although small, the percent and quantity of irrigated farmland has been increasing rapidly over the past decade. In 1997 and 2002 (the last two census years prior to 2007), only 0.3 and 0.5 percent of farmland was irrigated (USDA, 2007c). This trend of increasing irrigation in Tennessee parallels similar changes occurring throughout the southeastern United States. Figure 4-3 provides a map of the acres of irrigated land as a percent of county land in farms in 2002. Note that relative to other areas of the United States such as central California or eastern Arkansas, irrigation in the TVA region is limited.

In Tennessee, as in other states in the region, both livestock and crops are important contributors to the State's output: the top three single agricultural commodities are cattle, broilers, and cotton (USDA, 2008). Other important commodities in the State include corn, grains, hay, hogs, soybeans, and tobacco (USDA, 2007a). Table 4-1 lists the top 10 agricultural product groups (by market value) in Tennessee.

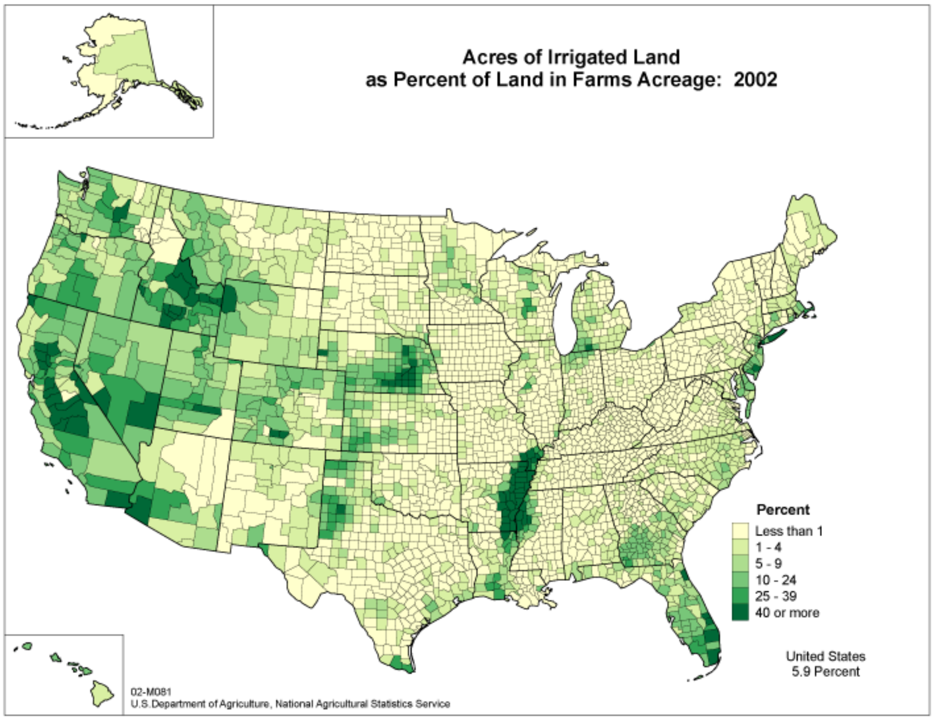

Figure 4-3
Acres of irrigated land as percent of county land in farms, 2002

Source: USDA (2002)

Table 4-1
Top 10 most valuable agricultural product groups produced in Tennessee

Product	Value ($000)	Acreage (if applicable)
Cattle and calves	$633,303	n/a
Poultry and eggs	$572,866	n/a
Grains, oilseeds, dry beans, and dry peas	$496,727	n/a
Nursery, greenhouse, floriculture, and sod	$325,079	59
Milk and other dairy products from cows	$180,503	n/a
Cotton and cottonseed	$147,468	504,057
Vegetables, melons, potatoes and sweet potatoes	$71,870	34,013
Tobacco	$70,634	20,109
Hogs and pigs	$33,797	n/a
Other crops and hay	$31,438	1,776,875
TOTAL	**$2,563,685**	**n/a**
Source: USDA 2007d. Census of Agriculture: Tennessee. Accessed on March 15, 2009 from http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Tennessee/index.asp.		

These ten commodity groups account for approximately 95 percent of the total value of agricultural output in Tennessee. It should be noted that these groupings mask the substantial diversity of crops grown within Tennessee and the TVA region. In total, there are 23 crops that have a commercial value of $1 million or more within Tennessee alone (U.S. Census, 2007). This diversity of crops will be important in assessing the vulnerability of agriculture in the TVA region to climate change, as well as the potential for the agricultural sector to adapt to future climate change.

4.2 Literature Review

This section summarizes recent research on the potential effects of climate change on agricultural resources in general with the purpose of evaluating anticipated effects of climate change on agriculture in the TVA region. Although there are few studies with such a narrow geographic focus, we use our judgment in this literature review to highlight the literature most applicable to TVA, summarize the conclusions of this literature, and suggest how they may be transferrable to the TVA context.

The literature has identified several broad lessons on the potential effects of climate change on U.S. agriculture (from Adams et al., 1999):

- Crops and livestock are sensitive to climate changes (temperature and precipitation) in both positive and negative ways.
- The impact of climate change on U.S. agriculture is mixed, and the emerging consensus from modeling studies is that the net effect on U.S. agriculture associated with a doubling of carbon dioxide (CO_2) may be small. Regional changes, however, may be significant.
- Consideration of adaptation and human response is critical to the accurate assessment of climate change impacts. Although the literature has generally agreed that agriculture is a sector that can adapt, there are some factors not included in modeling efforts that could change this conclusion. Thus inclusion of pests, diseases, and/or soil erosion may result in different conclusions.
- Better climate change forecasts, particularly at higher levels of spatial resolution, are crucial to improved assessments of the impacts of climate change on agriculture.
- The non-linear nature of economic impact curves associated with climate change and agricultural effects suggests that warming greater than considered in recent assessment efforts is likely to impose greater costs, including decreases in agricultural production.

In addition to the synthesis work of Adams et al. (1999), two IPCC reports and several other stand-alone documents address the intersection of climate change and agriculture. Note that a large body of literature also exists on the topic of agriculture's potential role in mitigating the impact of greenhouse gas emissions (for example, see Cole et al., 1997; McCarl and Schneider, 2001; Smith et al., 2007), which may be of interest to TVA. For a thorough treatment of this topic, see IPCC Working Group 3, Chapter 8 (2007). Further, a great deal has been written on the economic implications of changes in agricultural production, for example, effects on producer and consumer welfare, changes in regional output. In this review, we recognize the role of economic adaptations, but a detailed discussion of the full range of economic implications associated with climate change is beyond the scope of this effort. The interested reader can find more information on the economic dimension of climate change in Adams et al. (1999) and other reviews on this topic.

This section reviews: (1) the direct and indirect biophysical effects of climate change on crops and livestock, (2) the adaptive capacity of agriculture, and (3) the effect of climate change on agricultural production. Conclusions relevant to southeastern agriculture and more specifically to the area managed by TVA are reviewed in the discussion section that follows (Section 4.3).

4.2.1 Biophysical Effects of Climate Change on Crops and Livestock

Both direct and indirect dimensions of climate change affect crop yields and ultimately agricultural production. Direct effects include changes in temperature, precipitation timing and magnitude, soil moisture, and carbon dioxide concentrations in the atmosphere. It is important to note that evapotranspiration (ET) is the main driver of plant growth, and that ET is a function of the interaction of temperature and available moisture (precipitation). In general, as temperatures increase, plant growth (and yield) increases as long as soil moisture and nutrients are not constraining. This growth in yields or biomass continues until some maximum point is reached, at which time growth begins to decline. This pattern is frequently represented by growth or yield functions that have a dome shape. Within the TVA region, where temperature and moisture are not usually constraining, such a dome shape may be relatively flat, suggesting that changes in temperature may not elicit large changes in yields or biomass.

These direct effects associated with climate change in turn generate indirect effects that affect agriculture through changes in tropospheric ozone concentrations, increased incidence of pests and pathogens, and other effects. Although we review key findings of the literature here, these issues are discussed in greater depth by Rosenzweig and Hillel (2005), Reilly (2002), and Tilman et al. (2001).

Models that assess how climate change affects biophysical dimensions of crop growth and yields must first control for a wide range of factors unrelated to climate, such as technological improvements that have occurred and will continue to occur over time. Reilly and Fuglie (1998) analyze yield trends for 11 major crops in the U.S. for the period 1939 to 1994 and find a compound annual rate of growth of between 0.7 percent and three percent per year. More recently, Hicke and Lobell (2004) find that between 1970 and 2000, average annual corn yields have increased 1.5 percent and soybean yields 0.6 percent. The total effect of all factors (that is, technology, fertilizer application, improved seed stocks and management techniques, and climate effects) has increased U.S. commodity crop yields by one to two percent per year (Troyer, 2004).

4.2.1.1 Temperature

Researchers have employed two general approaches when studying the effects of temperature on crops and crop yields. First, studies have identified and statistically measured changes in yields as a function of temperature across space and time, controlling for other factors such as improvements in technology. The second approach, typically used by crop scientists, assesses crop yield functions experimentally under different temperature conditions, holding other factors such as water inputs and carbon dioxide levels constant.

Both types of studies have found positive (growth enhancing) and negative (growth retarding) effects of rising temperatures, with the outcome dependent on the timing and magnitude of temperature increases. For example, some studies indicate that increasing temperatures would benefit northern regions of the country due to longer growing seasons and warmer temperatures (Feng and Hu, 2004; Frumhoff et al., 2007; Wolfe et al., 2007). In the southern United States, warming will reduce killing frosts and thus decrease related crop losses (Gu et al., 2008). Overall, Huffman and Everson (1992) find that the length of the growing season has increased an average of two days per decade since 1950 in Canada and the United States, which has resulted in higher yields. Conversely, high temperatures, particularly during critical growth periods, speed plant development and reduce yields. Lobell and Asner (2003) conclude that yields of corn and soybeans from 1982 to 1998 were reduced 17 percent for each one degree Celsius of warm-temperature anomaly; and Lobell et al. (2006) find that, although fluctuations in climate over 20 years have not had large effects on the yields of 12 California crops overall, specific crops, including cotton, have suffered.

Increased temperatures also may affect livestock either through direct changes to weight gain or through the indirect effects on hay production (Adams et al., 1998; CCSP 4.3, 2008).

4.2.1.2 Precipitation

Water is a critical input to plant growth; either too much or too little is detrimental to crop yields. Increases in precipitation level and variability and changes in precipitation timing increase soil moisture and therefore benefit semi-arid areas, but may reduce yields in areas with excess water (Adams et al., 1999; Feng and Hu, 2004). Overall, water supply in much of the U.S. Corn Belt is projected to increase in most climate change scenarios, but water logging may occur in the summer months and access to fields for planting may be reduced in the spring (Rosenzweig et al., 2004). Indeed, Rosenzweig et al. (2002) find that heavy rainfalls reduced the value of the U.S. corn crop by $3 billion per year from 1951 to 1998. On the other hand, reductions in precipitation resulting from climate change in Kansas and Oklahoma may reduce grain yields by 30 to 40 percent (Tubiello et al., 2002).

Research focusing on the combined effects of precipitation and temperature has identified effects on the following:

- **Crop yields.** As noted by Adams et al. (1999), the literature on biophysical effects indicates that precipitation and temperature act either synergistically or antagonistically in terms of their effects on crop and livestock yields and that these effects vary considerably across regions. Achieving specificity in these conclusions is challenging because (1) transferring yield response findings under experimental settings to actual settings may not be reasonable, and (2) there is a great deal of uncertainty in temperature and precipitation models.
- **Crop water demand.** Researchers have also studied how the coupling of temperature and precipitation affects total crop water demand. Reilly (2002) considers a number of economic models in an assessment of how climate change will affect irrigation practices nationally. The study finds that agriculture's need for water nationally declines by 5 to 10 percent by 2030 and 30 to 40 percent by 2090, primarily due to increased precipitation and shortened growing seasons.
- **Soil moisture.** A function of soil type, rainfall patterns, and temperature patterns, soil moisture is a key determinant of crop yields. Soil moisture falls with increasing temperatures (due to increased evapotranspiration), but models have shown that increases in precipitation may compensate for these losses. In certain regions of the United States, decreases in precipitation coupled with increases in temperature could have pronounced downward effects on soil moisture (Cao and Woodward, 1998).

4.2.1.3 Carbon Dioxide

Carbon dioxide is a building block of crop yields. Within the general taxonomy of plants, the two most common photosynthetic types are C3 and C4 (SERC, 2009). Whether a plant is C3 or C4 has important bearing on how it will be affected by increased atmospheric carbon dioxide. Kimball et al's (2002) free-air CO_2 enrichment (FACE) study corroborates previous studies, demonstrating for several agricultural crops that increased CO_2 benefits C3 plants, which include wheat, rice, and soybeans, more than C4 plants, which include corn and sorghum. In experimental settings, research has indicated that, all else equal, increased atmospheric CO_2 increases plant growth (Allen et al., 1987). What remains uncertain, however, is whether higher CO_2 concentrations will increase net growth, after taking into consideration changes in temperature and precipitation (Long et al., 2006). Wolf and Erickson (1993) find that maximizing the benefit of higher CO_2 concentrations requires more nutrients and higher soil moisture, neither of which may be present in future years. As discussed below, increased atmospheric CO_2 also increases the incidence of pests and pathogens, which compete with crops and necessitate more herbicide application with the attendant environmental implications (Adams et al., 1999).

4.2.1.4 Extreme Events

General Circulation Models indicate that extreme weather events will occur with increasing frequency in future years. These events will increase both within individual years (for example, peak temperatures and rainfalls in any given year), and across multiple years (for example, multi-year droughts, extreme floods) (IPCC WG1, 2007). As crops tend to have a relatively narrow range of meteorological conditions in which they function well, small perturbations in historical patterns will have potentially dramatic effects on yields (CCSP 3.3, 2008; CCSP 4.3, 2008), while extreme changes, such as prolonged droughts, will have pronounced effects on productivity (Adams et al.,1999; Peet and Wolf, 2000). Rosenzweig et al. (2005) indicate that changes in water availability would have particularly significant impacts on water sensitive crops such as corn, soybeans, wheat, and sorghum. Wolfe et al. (2007) have evaluated the impact of flooding on agriculture, which leads to erosion of upland soils, increased runoff, and leaching of chemicals into surface and groundwater.

One of the anticipated extreme events effects will be the relationship between global climate change and the occurrence of the El Niño Southern Oscillation (ENSO) phenomenon. ENSO events impose economic costs on certain regions within the United States, and their effects on agriculture have been documented in Adams et al. (1995 and 2003). Adams et al. (1995) report a strong ENSO signal in the southeastern United States, and Tudhope et al. (2001) find that climate change may increase the strength of ENSO events. The implication for the TVA region is that an ENSO episode could be a potentially important extreme event for the area.

4.2.1.5 Indirect Effects

The indirect effects of climate change will also have an effect on crop yields and production. Research has demonstrated the negative impact of increasing concentrations of tropospheric ozone on crop yields (Hertstein et al., 1995) and that climate change will exacerbate these effects (Adams et al., 1986).

Increasing atmospheric CO_2 concentrations benefit both crops and weeds. At present, farmers in the United States lose a significant percentage of crops to weeds (Bridges 1992); and research has found that rising temperatures will allow weeds to expand their range north (Joyce et al., 2008) and allow pathogens and parasites to survive more readily through the winter months (Frumhoff et al., 2007). Wolfe et al. (2007) point out that rising CO_2 concentrations will necessitate more pesticide and herbicide application, which will impose environmental and economic costs.

4.2.2 The Role of Human Response and Adaptation to Climate Change

Human adaptation to economic, physical, and institutional conditions plays a significant role in shaping the agricultural landscape. Agriculture is an industry that deals with substantial risk from a range of sources. Both costs (that is, costs of inputs to the production process such as gasoline, seeds, or fertilizer) and revenues (that is, market prices of crop outputs) are highly variable from year to year; and seasonal weather patterns – which directly affect crop yields – vary widely. Increases in climatic variability will increase the inherent risks in agriculture; as with other risks, farmers will adapt to climate change using a variety of potential strategies.

The more farmers are able to adapt, the less severe the effects of climate change will be. Adaptive strategies include adaptation at the field level, the farm level, or the sectoral (for example, regional or national) level. These strategies are reviewed in depth in IPCC WG2 (2007, Chapter 14). Each adaptation can lessen potential losses from climate change and may improve productivity in some instances (Adams et al., 1999). Failure to account for adaptation in economic models of climate change impacts may overestimate impacts attributed to climate change. For example, Adams et al. (1995) estimate a net gain in U.S. wheat supply (4 to 15 percent) given falling wheat yields under a scenario where CO_2 is doubled. In their model, falling yields cause increased market prices, which prompts more land to be converted to wheat acreage and therefore causes overall production to increase. Similarly, Mendelsohn et al. (1994) demonstrate the important role of adaptations in responding to climate by applying a model that uses real world data on profits and land rents in the face of climate variability.

While the role of adaptations needs to be included in assessments of agricultural effects, it is also important to note that in some instances the incremental stress added by climate change may overly burden some farming operations such that adaptation is not possible and the farm, or farming community, is unable to remain profitable. If the displaced agricultural activity shifts to another part of the United States or world, some may view this shift as a form of adaptation on a larger scale; however, such regional shifts cause labor and other resources to be displaced and therefore may reduce welfare in certain regions.

4.2.2.1 Field Level Responses

At the field level, farmers may alter their application of fertilizer, irrigation patterns, or timing of planting or other cropping activities. Field level changes can occur on short time scales, such as within individual seasons, and therefore provide a highly flexible response to seasonal fluctuations in precipitation and temperature conditions. Smit et al. (1996) study the adaptive behavior of farmers in Ontario, Canada to changes in climate over a six-year period. They find that many of the farmers adapted to variable conditions with strategic adaptations, most often in the face of frequent dry years. Brown et al. (2000) explore the feasibility of converting agricultural land in the Missouri-Iowa-Nebraska-Kansas region to the production of switchgrass as a biomass energy crop under two different climate change scenarios. They find that with increased temperature and precipitation, switchgrass yields increase over the entire region while traditional crop yields decrease in the south and east. Additionally, they find that switchgrass reduces runoff and soil erosion in the region and conclude that transitioning to switchgrass may be a suitable adaptation strategy.

4.2.2.2 Farm Level Responses

Farm level adaptive responses include individual farmers changing crop mixes, converting to different irrigation systems, or changing the timing of farm operations (Schimmelpfennig et al., 1996, Kaiser et al., 1993). These adaptations often require more significant capital investments and occur over a longer time horizon than those at the field level. Given the percentage of agriculture in Tennessee that is rain-fed, one farm level response will likely be converting rain-fed fields to irrigated fields as temperature and precipitation patterns become less predictable or drought conditions become more prevalent. Connor (2004) discusses issues involved in designing cropping systems that are economically as well as environmentally acceptable, considering soil water storage and salinity issues. Specifically Connor discusses the search for cereal farming systems that retain autumn and winter rainfall and reduce drainage through the soil and lower saline tables. Smit and Skinner (2002) note that adaptation activities (for example, water conservation and conservation tillage) are not typically taken as discrete actions, but evolve as a set of dynamic actions over time.

4.2.2.3 Sectoral Level Responses

Sectoral adaptive responses include local, state, or Federal government policy changes, creation of incentive programs, or utilization of other policy mechanisms (see Goodwin, 2003, for example). These broader approaches to managing the effects of climate change may potentially trigger larger scale changes to the agricultural landscape. The recent subsidies on inputs to the ethanol production process have led farmers to convert large acreages to corn, illustrating the potential effect of subsidies on the distribution of crops. This particular incentive has had wide-ranging effects, from increased water consumption on agricultural fields to impacts on international agricultural markets. In another example noted by Adams et al. (1999), changes in Bureau of Reclamation policies for managing water could shape water management in the arid western United States in the face of a changing climate. Rosenzweig and Tubiello (2007) suggest that policymakers exercise caution when defining carbon mitigation policies involving agriculture. Given that farm level and community responses are likely to be site specific, top-down policies may thwart the ability of farmers to respond effectively to climate change.

4.2.3 Effects of Climate Change on Agricultural Production

Agricultural production reflects the interaction of crop yield changes with changes in crop acreage. Section 4.1.1 reviews changes in crop yields due to changes in climatic variables. As noted by Adams et al. (1990 and 1999), the distribution of changes in agricultural production attributable to climate change varies widely across regions and crops. Given that changes in production reflect economic processes driven by many factors (including biophysical changes in crops and changes in growing season), researchers have employed economic models to evaluate how cropping distributions will change. In this section, we first review the primary conclusions of research that has focused on biophysical effects and then review conclusions of the economics literature. The results of both biophysical and economic studies rely heavily upon the selected climate change scenario, which generates estimated changes in yields used to parameterize the biophysical component of the economic models. Consistent with the reference case presented in

Chapter 2, we focus on studies that considered climate change scenarios similar to IPCC Scenario A1B.

The two most commonly used methods to model the economic impacts of climate change are the Ricardian and empirical approaches. The Ricardian approach examines how crop production varies in regions of different climates and then infers the effect of climate from these differences (Mendelsohn et al., 1994). The approach explicitly embeds farm adaptations as found in the pooled (time series and cross sectional) data. Using these data, it is possible to forecast how climate changes affect profits and production in future years (Mendelsohn et al., 1994; Mendelsohn and Reinsborough, 2007). However, the approach has disadvantages that have been noted by Schlenker et al. (2005) and Adams (1999), such as the inability to address changes in weather beyond the variability found in the underlying data. On the other hand, empirical models simulate future changes in production by assuming a specific objective (for example, farm profits) and then maximizing this objective subject to a set of constraints that represent the physical and socioeconomic system within which farmers make production decisions. This approach is useful in climate research because it can consider potential impacts of future scenarios that have not yet occurred. Its disadvantage relative to the Ricardian approach is that economic adaptations must be specified and embedded in the model by the analyst. Both techniques have applicability, however, as noted by Adams (1999).

Studies that adopt assumptions generally aligned with the A1B scenario, such as Adams et al. (1998), indicate that agriculture in northern regions of the United States will thrive under improved growing conditions and higher crop prices, whereas supplies from southern states will decline. Figure 4-4 displays these results geographically for the United States given an increase in CO_2 concentrations to 530 ppm, and uniform nationwide increases in temperatures by 2.5 degrees Celsius and precipitation by seven percent. Note that although these values closely match the 2050 CO_2 forecast in the reference case, both the temperature and precipitation increases are higher. In the reference case, winter precipitation averaged across regions is forecast to increase roughly seven percent by 2050, but summer precipitation values decrease. Adams et al. also conclude that if temperature and precipitation changes are more severe than seen in a CO_2 doubling scenario, crop production losses will be more extensive, particularly in the southern United States.

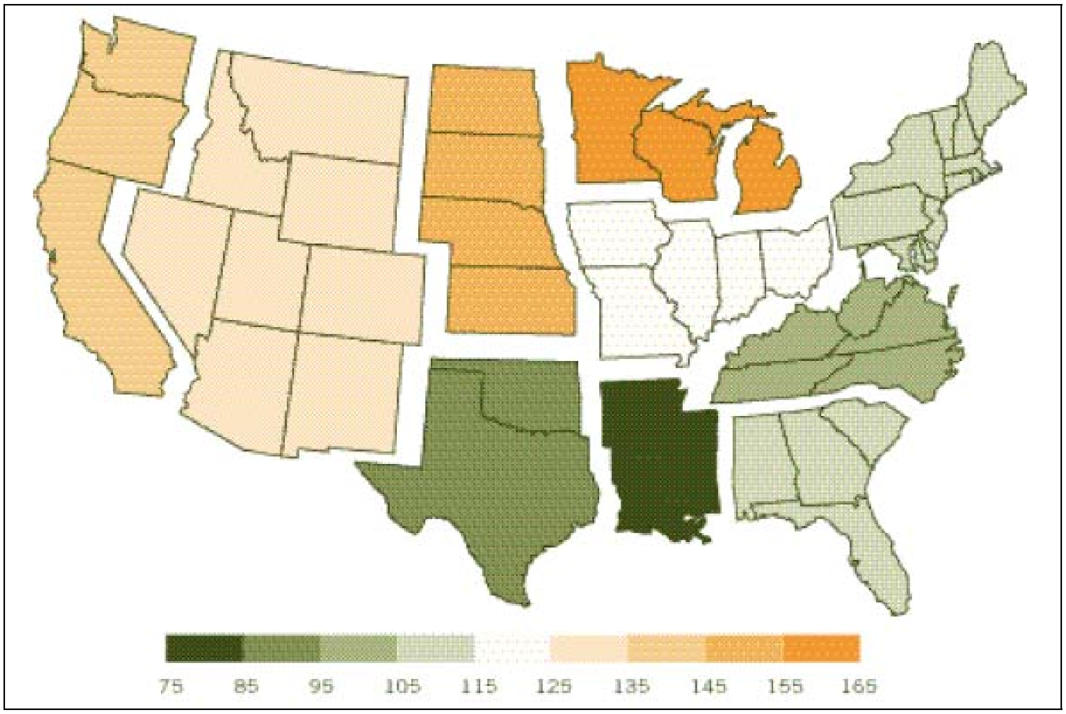

Figure 4-4
Modified crop production effects under one climate change scenario: 2.5ºC increase in temperature; 7% increase in precipitation (current baseline = 100)

Source: Adams et al. (1999)

In a more recent study, Massetti and Mendelsohn (2009) use a Ricardian modeling approach based on historical climatological and agronomic data to evaluate the effects on agricultural land value given uniform nationwide increases in temperature of 2.7 degrees Celsius and precipitation increases of eight percent. The authors find that land value changes in the TVA region depend heavily on the specified climate model. In Figure 4-5, observe that land value changes in the TVA region for the Hadley III climate model are almost entirely negative, whereas the PCM climate model forecasts a uniformly positive effect. These results show that the effects could be either positive or negative and corroborate the results in Figure 4-4 and elsewhere that the effects of climate change on agriculture are uncertain in the TVA region.

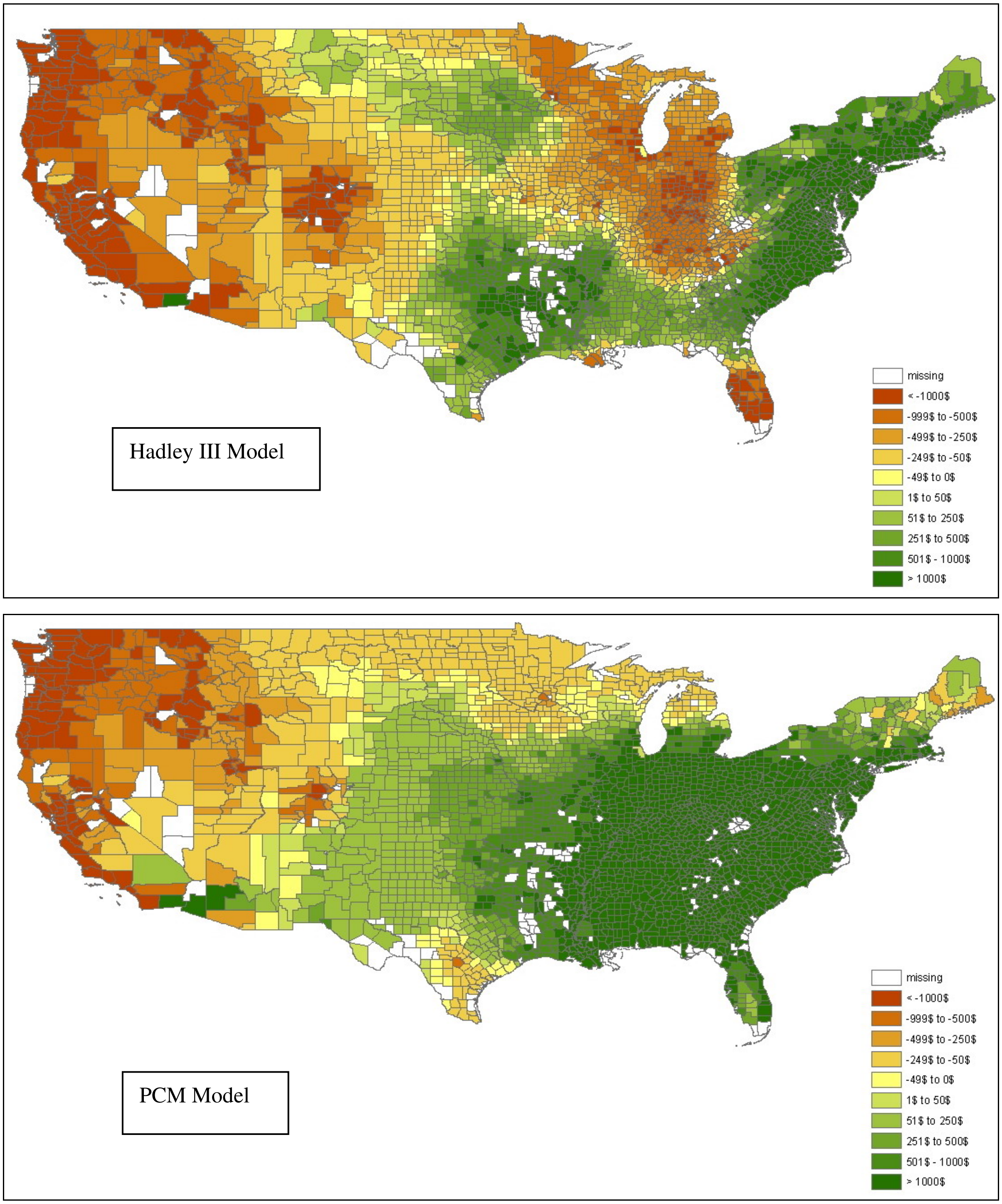

Figure 4-5
The impact of climate change on land value in the U.S. (2000$ per hectare), Hadley iii and PCM climate Models: 2.7ºC increase in temperature; 8% increase in precipitation

Source: Massetti and Mendelsohn (2009)

4.2.4 Environmental Effects of Changes in Agricultural Production

Changing agricultural practices in response to climate change are expected to affect the natural environment. Increased application of chemicals (that is, pesticides, herbicides, and fertilizer) to manage weeds coupled with increased flooding frequency will increase pollutant runoff into water bodies. For example, in a study of agriculture in the Chesapeake Bay drainage, Reilly (2002) finds that the load of excess nitrogen into the Bay due to corn production increased by 17 to 31 percent (in two scenarios) over current levels. Expanding agriculture to previously unproductive lands with higher slopes, along with higher runoff, will increase erosion of topsoil (Wolfe et al., 2007). As agriculture expands into areas previously occupied by wetlands, sensitive populations of fish and wildlife will be threatened (Pioani and Johnson, 1993). According to the U.S. EPA (2008), agriculture already generates roughly 8.6 percent of total U.S. greenhouse gas emissions; changing farming practices in response to climate change will affect emissions, although how is uncertain.

4.3 Discussion

Preceding sections of this chapter review 1) the state of agriculture in the TVA region and 2) selected literature on the effects of climate change on agriculture. Although we could not identify any studies specific to the TVA region, we feel that the findings in the large volume of literature reviewed here are sufficiently robust to suggest possible effects of climate change on agriculture within this area. Findings from this literature are also used to identify areas of research needed to support these qualified conclusions. These areas are discussed in the following sections.

4.3.1 The Effect of Climate Change on the TVA Region

A common finding in the extant literature on agriculture is that there will be regional winners and losers. This mixed picture is expected, given that changes in climate will vary across the landscape and crop growth may currently benefit from or be constrained by weather in some settings. Most studies indicate that the regions likely to benefit from climate change (the winners) are associated with regions in more northerly latitudes, in both the United States and globally, primarily because the modeled crops benefit from the increased heat units associated with rising temperatures.

An implication of this regional winners and losers finding for the TVA region is that it falls between the “winners” and “losers” demarcation within the United States (see, for example, Figure 4-4). The lack of a clear direction on the aggregate effects of climate change on agriculture in this region is because (1) most assessments fail to consider the wide range of crops found in some areas (which adds to resiliency), and (2) the lack of spatial resolution in these assessments tends to compound, or add uncertainty to, region-specific forecasts. The coarse level of spatial resolution in most agricultural studies creates challenges in regional or sub-regional analyses such as those involved with the TVA region.

The above observations suggest that in the TVA region, information on crop mixes currently grown and future crop mixes under climate change need to be explored. The literature reviewed here documents ranges of crop and livestock yield effects associated with mid-range temperature and precipitation changes. As noted in the literature review, moderate changes in temperature and precipitation, combined with the “fertilizer effect” of increased CO_2, generally lead to slight increases, on average, in crop yield and production. These effects typically are measured against base case climate assumptions that span large geographical areas because of the lack of spatial resolution in General Circulation Model forecasts. An assessment of these TVA region-specific crops under updated climate assumptions can indicate whether the region is at risk.

Another implication of the findings reported in the extant literature concerns the use of irrigation. Most studies for the United States forecast an expansion of irrigated acreage, particularly in the arid western portions of the United States. However, irrigation is expanding into non-traditional areas. As noted in section 4.1, currently only three percent of the agricultural acreage in the TVA region is irrigated. However, as is the pattern through much of the eastern United States, irrigation is increasing. Changes in the frequency of extreme events, such as drought, are drivers of the current trend toward reliance on irrigation, a trend that is likely to accelerate under future climate scenarios. Furthermore, increases in water use have historically contributed to productivity growth; if this growth is to be sustained, increased irrigation will be necessary. Whether adequate water resources will be available for an expansion of irrigation is an important research issue. Further, expanded irrigation would also increase agriculture’s demand for electricity. While agriculture nationally is a small user of energy, in areas where it relies on center pivot or other pressurized systems, its consumption can be substantial. To the extent that additional irrigated acreage in the TVA region relies on these technologies, increases in energy consumption in the agricultural sector may be substantial.

4.3.2 Data and Modeling Gaps

As noted previously, a major challenge in assessing the effects of climate change on agriculture within the TVA region is the lack of sufficient spatial resolution to measure crop and livestock effects. There is a growing literature on downscaling, in which techniques are developed to take General Circulation Model forecasts and translate them into climate forecasts with greater resolution (see, for example, Mearns et al., 2001; Adams et al., 2003; Gaffin et al., 2004). Regional or finer scale climate change forecasts are needed to understand not only the effects of climate change on agriculture but on other sectors and resources at risk, such as water resources and forestry.

Data on irrigation use by agriculture and future trends in such use are needed to assess the role of irrigation in mitigating impacts of climate change. Some data are obtainable from the Census of Irrigated Agriculture but because of the relatively low level of current use, the range of possible irrigation technologies and future demand for irrigation water may not be easily identified from such sources.

4.3.3 Recommendations for Future Research

Recommendations for future impacts research include:

- **A focused analysis of specific crops under finer resolution of climate forecasts.** The TVA region features a wider range of crops than are included in most available assessments of climate change. The presence of multiple crops creates adaptation opportunities for farmers if they adjust crop mixes in the face of a changing climate. However, the ability to exploit these altered crop mixes depends on how these crops respond to climate change. Information on how TVA region crops may be affected by climate change is important in assessing potential vulnerabilities within the TVA region. Such an assessment will require both improved understanding of the physiological effects of climate on these crops as well as likely changes in local climate. The latter information can be obtained by finer spatial resolution in General Circulation Model climate forecasts or improved downscaling procedures of such outputs.
- **A focused assessment of extreme events and the impacts on agriculture.** Extreme events, such as floods and droughts, impose large costs to agriculture. Research indicates that these events are expected to increase under climate change. Information on the frequency of such adverse events is needed for the TVA region. In addition, research indicates that the TVA region is likely to experience more ENSO events under a warming climate; ENSO events typically involve more floods and droughts, depending on the ENSO phase. Adaptations in the face of these extreme events are likely to include changes in crop mix, as well as reliance on irrigation. An assessment of adaptation possibilities within the region under extreme events can be useful in understanding potential vulnerabilities.
- **A survey of irrigation use and assessment of potential for irrigated agriculture.** Irrigated crop acreage is increasing within the southeastern United States, motivated in part by the desire to increase crop yields. Irrigated acreage in the TVA region has also been increasing, but the area is still predominantly rain-fed. Warming is expected to increase crop water demand, along with increased drought frequency. Together, these effects are hypothesized to increase the rate of adoption of irrigation. A survey of current irrigation patterns within the TVA area, as well as the southeast, can be instructive in understanding the potential for increased irrigation in the future. Such information would also be useful in implementing a water demand assessment, as is proposed in Chapter 3.

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5
POTENTIAL EFFECTS OF CLIMATE CHANGE ON FOREST RESOURCES

5.0 Introduction

Forests cover a large portion of the TVA region, and the forest products industry is a major component of the regional economy in the TVA region. Climate change may affect a variety of forest properties such as growth, composition, and distribution, which in turn may affect the forest products industry. This literature review describes the potential effects of climate change on forest resources, both generally and in the TVA region.[6]

In general, the literature indicates that the effects of climate change on forests will vary depending on the future climate scenario. Specifically, the effects of climate change on forests will vary considerably depending on the magnitude and direction of changes in temperature, precipitation, and CO_2 concentration.

5.1 Characterization of Forests and the Forest Products Industry in Tennessee

The southern United States includes 215 million acres of forestland, accounting for approximately 29 percent of all forestland in the country (Conner and Hartsell, 2002).[7] This section provides an overview of the forests in the TVA region and a detailed description of the forests and the forest products industry in Tennessee.

5.1.1 Overview of Forests in the TVA Region

Table 5-1 presents the total area of forestland and timberland aggregated by state for the counties intersecting the TVA region. Figure 5-1 presents forest cover by forest type within the TVA region. As reported in Table 5-1, there are approximately 33.1 million acres of forestland in the TVA region, more than 40 percent of which is located in Tennessee. Of the total forestland in the

[6] Chapter 6 describes the potential impacts of climate change on ecosystems, including forested ecosystems. This chapter focuses on climate change-related impacts on the forest resources (that is, the trees).

[7] Forestland is defined as land at least 10 percent stocked by forest trees of any size, or formerly having had such tree cover, and not currently developed for non-forest use. The minimum area considered for classification is one acre.

region, approximately 97 percent (31.9 million acres) is classified as timberland.[8] Oak/hickory is the dominant forest type in the TVA region, representing approximately 20 percent of the total forestland. Secondarily, the mixed upland hardwoods, loblolly pine, and chestnut oak/black oak/scarlet oak forest types represent significant portions, with each forest type accounting for between 8 and 13 percent of the total forestland of the forestland in the TVA region.

Table 5-2 presents total growing stock volume on forestland and timberland within counties intersecting the TVA region, aggregated by state.[9] As reported in Table 5-2, there are approximately 57.5 billion cubic feet of growing stock in the TVA region, more than 40 percent of which is located in Tennessee. Of the total growing stock volume, approximately 94 percent (54.2 billion cubic feet) is located on timberland. Oak/hickory forests have the most growing stock volume of any forest type in the TVA region (approximately 22 percent of the total). Secondarily, the loblolly pine, chestnut oak/black oak/scarlet oak, mixed upland hardwoods, and yellow-poplar/white oak/northern red oak forest types represent significant portions (roughly 10 percent each) of the growing stock volume in the TVA region.

Given that Tennessee has more forestland and growing stock volume in the TVA region than any other state, the remainder of this section focuses on Tennessee forests and the forest products industry in the State. We assume that the characterization of Tennessee forests and the associated forest products industry is sufficiently representative of the forests and the forest products industry throughout the TVA region.

[8] Timberland refers to forestland producing or capable of producing more than 20 cubic feet of merchantable wood per acre per year and not withdrawn from timber harvesting by law.

[9] Growing stock volume is defined as the net volume of growing stock trees (live trees of commercial species excluding rough or rotten trees) with a diameter-breast-height of at least five inches from a one-foot stump to a minimum four-inch top diameter. Net volume refers to gross volume less any rough or rotten limbs.

Table 5-1
Total forestland and timberland within counties intersecting the TVA region by forest type and state

STATE	OAK/ HICKORY	MIXED UPLAND HARD-WOODS	YELLOW-POPLAR/ WHITE OAK/ NORTHERN RED OAK	EASTERN REDCEDAR/ HARD-WOODS	VIRGINIA PINE/ SOUTHERN RED OAK	SWEETGUM/ YELLOW-POPLAR	SWEETGUM/ NUTALL OAK/ WILLOW OAK	LOBLOLLY PINE
TOTAL FOREST AREA (ACRES)								
Alabama	774,176	385,042	107,126	70,389	75,078	234,065	112,094	749,468
Georgia	236,252	97,667	168,654	3,002	109,788	44,186	0	148,066
Kentucky	623,264	242,827	57,274	33,613	16,271	35,199	0	34,634
Mississippi	569,610	840,872	112,821	57,035	0	492,884	340,065	2,468,834
North Carolina	632,232	490,216	329,299	0	7,719	0	0	7,719
Tennessee	3,417,020	1,824,181	769,490	336,254	285,013	582,024	97,034	534,500
Virginia	294,735	346,527	222,709	4,898	22,512	0	0	0
Total	**6,547,288**	**4,227,332**	**1,767,374**	**505,191**	**516,381**	**1,388,358**	**549,193**	**3,943,221**
TIMBERLAND AREA (ACRES)								
Alabama	774,176	379,161	101,245	70,389	75,078	234,065	112,094	739,063
Georgia	218,157	79,572	140,004	3,002	97,724	44,186	0	148,066
Kentucky	594,632	242,827	57,274	33,613	16,271	35,199	0	34,634
Mississippi	569,610	836,654	112,821	57,035	0	488,948	333,815	2,460,351
North Carolina	525,071	413,629	291,005	0	7,719	0	0	7,719
Tennessee	3,324,044	1,807,848	689,677	331,744	273,749	563,706	86,189	532,563
Virginia	294,735	346,527	222,709	4,898	22,512	0	0	0
Total	**6,300,425**	**4,106,218**	**1,614,736**	**500,681**	**493,054**	**1,366,104**	**532,098**	**3,922,396**

Table 5-1 (continued)
Total forestland and timberland within counties intersecting the TVA region by forest type and state (cont.)

STATE	SLASH PINE	CHESTNUT OAK/ BLACK OAK/SCARLET OAK	CHESTNUT OAK	EASTERN HEMLOCK	EASTERN WHITE PINE/ NORTHERN RED OAK	OTHER FOREST TYPES	TOTAL
TOTAL FOREST AREA (ACRES)							
Alabama	0	148,223	167,387	12,227	0	867,418	3,702,694
Georgia	0	323,733	176,011	10,956	71,498	478,827	1,868,639
Kentucky	0	69,829	38,866	0	0	688,172	1,839,949
Mississippi	5,827	22,182	12,501	0	0	1,868,669	6,791,300
North Carolina	0	560,459	160,389	17,941	101,662	666,877	2,974,512
Tennessee	0	1,079,183	743,589	50,484	40,509	4,160,965	13,920,245
Virginia	0	347,717	110,315	0	30,867	614,758	1,995,039
Total	**5,827**	**2,551,326**	**1,409,058**	**91,608**	**244,535**	**9,345,686**	**33,092,379**
TIMBERLAND AREA (ACRES)							
Alabama	0	148,223	167,387	6,347	0	859,526	3,666,755
Georgia	0	289,051	165,050	4,924	65,466	472,795	1,727,997
Kentucky	0	69,829	38,866	0	0	659,119	1,782,264
Mississippi	5,827	22,182	12,501	0	0	1,865,857	6,765,601
North Carolina	0	556,220	160,389	17,941	101,662	559,545	2,640,900
Tennessee	0	1,004,914	728,397	33,990	40,509	3,968,407	13,385,737
Virginia	0	347,717	104,158	0	30,867	598,119	1,972,244
Total	**5,827**	**2,438,136**	**1,376,749**	**63,201**	**238,504**	**8,983,369**	**31,941,499**

Source: Miles, Patrick D. Jul-20-2009. Forest inventory mapmaker web-application version 4.0. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. [Available only on internet: www.ncrs2.fs.fed.us/4801/fiadb/index.htm]

Note: The other forest types category includes forest types such as, eastern white pine, shortleaf pine, pitch pine, red spruce, and eastern redcedar. Although other forest types combine to represent approximately 28 percent of the total forestland, individually, none of the other forest types represents more than three percent of the total forestland in the TVA region.

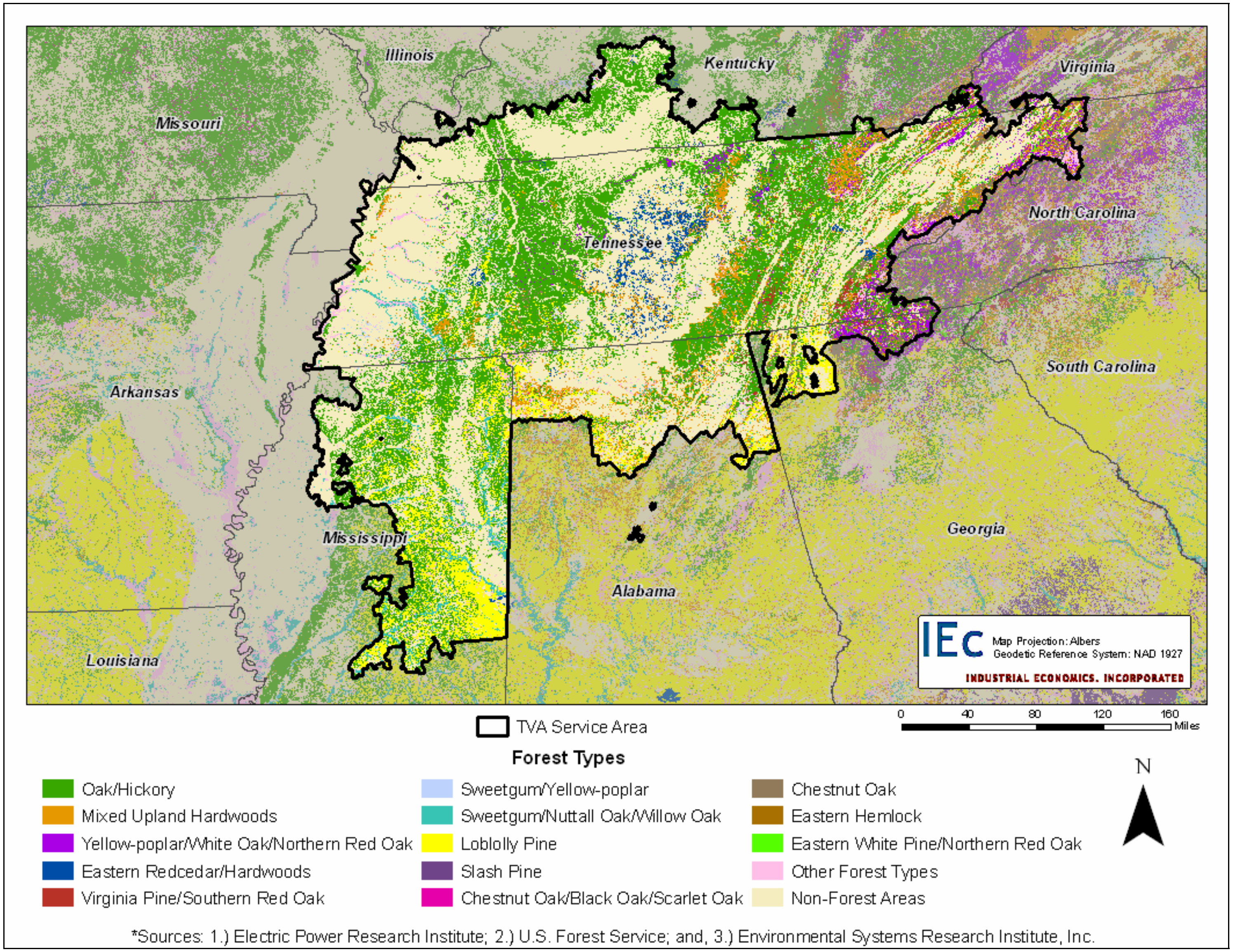

Figure 5-1
Forest cover within the TVA region by forest type

Table 5-2
Growing stock volume on forestland and timberland within counties intersecting the TVA region by forest type and state

STATE	OAK/ HICKORY	MIXED UPLAND HARDWOODS	YELLOW-POPLAR/ WHITE OAK/ NORTHERN RED OAK	EASTERN REDCEDAR/ HARD-WOODS	VIRGINIA PINE/ SOUTHERN RED OAK	SWEETGUM/ YELLOW-POPLAR	SWEETGUM/ NUTALL OAK/ WILLOW OAK
TOTAL FOREST GROWING STOCK VOLUME (CUBIC FEET)							
Alabama	1,272,108,906	246,926,939	196,605,484	60,168,554	54,390,489	309,893,458	253,318,907
Georgia	481,329,053	152,828,488	425,120,606	0	182,032,087	52,743,169	0
Kentucky	1,114,571,725	341,557,217	66,297,968	38,748,043	37,518,044	43,390,058	0
Mississippi	850,639,838	850,647,316	214,529,597	31,102,394	0	503,089,957	702,992,647
North Carolina	1,660,627,889	1,120,416,576	1,292,891,719	0	5,550,254	0	0
Tennessee	6,619,732,361	2,289,923,058	1,788,773,732	230,689,512	441,964,481	1,003,757,168	267,415,068
Virginia	639,460,638	379,190,079	534,715,297	741,266	23,123,301	0	0
Total	**12,638,470,411**	**5,381,489,673**	**4,518,934,404**	**361,449,769**	**744,578,656**	**1,912,873,811**	**1,223,726,621**
TIMBERLAND GROWING STOCK VOLUME (CUBIC FEET)							
Alabama	1,272,108,906	240,486,586	184,628,469	60,168,554	54,390,489	309,893,458	253,318,907
Georgia	447,180,232	81,317,446	305,845,985	0	158,057,833	52,743,169	0
Kentucky	1,024,382,178	341,557,217	66,297,968	38,748,043	37,518,044	43,390,058	0
Mississippi	850,639,838	849,462,323	214,529,597	31,102,394	0	503,089,957	692,957,473
North Carolina	1,371,201,907	971,660,511	1,026,790,428	0	5,550,254	0	0
Tennessee	6,390,006,272	2,254,090,940	1,505,207,544	229,432,304	427,277,837	920,995,066	213,075,225
Virginia	639,460,638	379,190,079	534,715,297	741,266	23,123,301	0	0
Total	**11,994,979,971**	**5,117,765,102**	**3,838,015,289**	**360,192,561**	**705,917,758**	**1,830,111,708**	**1,159,351,605**

Table 5-2 (continued)
Growing stock volume on forestland and timberland within counties intersecting the TVA region by forest type and state (cont.)

STATE	LOBLOLLY PINE	CHESTNUT OAK/ BLACK OAK/ SCARLET OAK	CHESTNUT OAK	EASTERN HEMLOCK	EASTERN WHITE PINE/ NORTHERN RED OAK	OTHER FOREST TYPES	TOTAL
TOTAL FOREST GROWING STOCK VOLUME (CUBIC FEET)							
Alabama	988,618,626	279,766,954	321,483,599	39,683,330	0	1,320,180,297	5,343,145,543
Georgia	216,618,732	631,775,738	418,951,635	32,386,212	243,247,647	875,480,770	3,712,514,138
Kentucky	45,864,514	102,116,780	69,541,723	0	0	1,133,401,151	2,993,007,223
Mississippi	3,618,340,088	28,255,105	13,128,432	0	0	2,182,912,395	8,995,637,769
North Carolina	13,028,670	1,334,962,306	392,404,364	74,637,430	341,557,860	1,978,397,049	8,214,474,118
Tennessee	592,629,533	2,432,568,746	1,728,069,133	198,391,317	98,201,378	6,885,908,538	24,578,024,026
Virginia	0	762,160,684	216,261,720	0	30,078,119	1,058,047,829	3,643,778,934
Total	**5,475,100,163**	**5,571,606,314**	**3,159,840,607**	**345,098,289**	**713,085,005**	**15,434,328,028**	**57,480,581,751**
TIMBERLAND GROWING STOCK VOLUME (CUBIC FEET)							
Alabama	951,329,691	279,766,954	321,483,599	18,044,224	0	1,296,396,934	5,242,016,771
Georgia	216,618,732	552,652,860	399,135,876	12,096,895	225,647,296	870,493,278	3,321,789,602
Kentucky	45,864,514	102,116,780	69,541,723	0	0	1,045,205,890	2,814,622,414
Mississippi	3,607,362,197	28,255,105	13,128,432	0	0	2,182,287,629	8,972,814,946
North Carolina	13,028,670	1,318,059,321	392,404,364	74,637,430	341,557,860	1,560,550,884	7,075,441,630
Tennessee	585,716,469	2,254,073,940	1,696,949,305	112,477,939	98,201,378	6,505,592,849	23,193,097,068
Virginia	0	762,160,684	216,224,101	0	30,078,119	1,028,105,641	3,613,799,127
Total	**5,419,920,273**	**5,297,085,645**	**3,108,867,400**	**217,256,489**	**695,484,653**	**14,488,633,104**	**54,233,581,558**

Source: Miles, Patrick D. Jul-20-2009. Forest inventory mapmaker web-application version 4.0. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. [Available only on internet: www.ncrs2.fs.fed.us/4801/fiadb/index.htm]

Note: The other forest types category includes forest types such as, eastern white pine, shortleaf pine, pitch pine, red spruce, and eastern redcedar. Although other forest types combine to represent approximately 27 percent of the total growing stock volume on forestland, individually, none of the other forest types represents more than four percent of the total growing stock volume in the TVA region.

5.1.2 Tennessee Forest Composition and Structure

Approximately 53 percent (13.92 million acres) of Tennessee is forested (Miles, 2009). The amount of forestland in Tennessee has remained relatively constant in the last five to ten years, though it has increased over the past century. Tennessee forests contain a variety of hardwood and softwood species including, among others: yellow poplar, oak, hickory, maple, beech, birch, black locust, shortleaf pine, Virginia pine, loblolly pine, eastern redcedar, and cypress. Red maple is the most common species in the State in terms of stem number followed by blackgum, yellow poplar, and eastern redcedar. White oak and yellow poplar are the most abundant species in terms of volume followed by chestnut oak, red maple, scarlet oak, and sweetgum. Finally, white oak, red maple, and yellow poplar are the most widely distributed species in the State (Oswalt et al., 2009).

The majority of forestlands in Tennessee are made up of hardwood forest types (Oswalt et al., 2009). In general, softwood forest types are restricted to the Appalachian Mountains and the loess and southeastern plains. The oak-hickory forest type is dominant in Tennessee representing approximately 74 percent (10.1 million acres) of all forested areas in the State. The oak-hickory forest type is also the most widely distributed forest type in the State. Secondarily, mixed upland hardwood, oak-pine, eastern redcedar-hardwood, and loblolly pine forest types represent significant portions of Tennessee forestlands.

Forest composition is constantly changing in Tennessee due to forest succession, natural disturbance events, and forest management. Between 1999 and 2004, reductions occurred in the abundance of several oak and pine species including black oak, northern red oak, chestnut oak, scarlet oak, Virginia pine, pitch pine, shortleaf pine, eastern white pine, and loblolly pine.[10] Conversely, the abundance of several hardwood species including black cherry, yellow poplar, sugar maple, red maple, and sweetgum, increased over the same time period (Oswalt et al., 2009).

In general, forests in Tennessee are increasing in age and progressing to later-successional stages. Specifically, the peak age class in Tennessee forests in 2004 was the 56-60 year age class, up from the 46-50 year age class in 1999. The majority of forestland in the State is aged 40 to 80 years and is in mid-to-late successional stages. Only 12 percent of Tennessee forests are in early successional stages (Oswalt et al., 2009)

5.1.3 Tennessee Forest Ownership and Management

The majority (85 percent) of Tennessee forestland is privately owned, including both industrial and non-industrial private landowners. The remaining 15 percent of forestland is publicly owned or managed. Specifically, five percent of forestland in Tennessee is federally owned and managed as national forest, five percent is otherwise federally owned, and five percent is owned or managed by State and local entities (Oswalt et al., 2009).

[10] The decreases in pine species between 1999 and 2004 are due primarily to a southern pine beetle epidemic between 1999 and 2002.

Of the forested areas in Tennessee, approximately 97 percent (13.38 million acres) are classified as timberland. Yellow poplar and oak species represent the most abundant growing stock tree species on timberlands in the State. Similar to forestlands, timberlands are dominated by the oak-hickory forest type, which represents 74 percent (9.9 million acres) of all timberlands in the State. Secondarily, the loblolly-shortleaf pine forest type represents a significant portion of the timberlands in the eastern portion of Tennessee, while bottomland hardwoods (elm-ash-cottonwood and oak-gum-cypress forest types) represent a significant portion of the timberlands in the western portion of Tennessee. Between 1999 and 2004 there were significant decreases in the amount of loblolly-shortleaf pine, oak-pine, and maple-beech-birch timberlands and significant increases in oak-hickory timberlands (Oswalt et al., 2009).[11]

Between 1999 and 2004 approximately 8 percent (1.1 million acres) of Tennessee timberlands were harvested with an average of 783 million cubic feet of timber (29 percent softwood, 71 percent hardwood) removed annually. The majority of timber harvests in Tennessee between 1999 and 2004 were partial harvests (approximately 150,000 acres annually). Secondarily, clearcuts were utilized on a significant portion of harvested areas. Following timber harvest, the majority of forests in Tennessee were naturally regenerated (that is, were not planted). Despite their economic importance, pine plantations represent only a small portion of timberlands in Tennessee (a total of 334,000 acres in 2004, concentrated mainly in the west and west central regions of the State (Oswalt et al., 2009).

5.1.4 The Value of the Forest Products Industry in Tennessee

The forest products industry represents a significant portion of the Tennessee economy. In 2004, 450 mills and wood-processing plants employed roughly 31,700 individuals with an estimated payroll of $1.0 billion. The value of Tennessee forest product shipments in 2004 exceeded $6.9 billion, while the total value of the Tennessee forest products industry was estimated to be $16.1 billion in 2001 (Oswalt et al., 2009).

5.1.5 The Role of Disturbance in Tennessee Forests

Disturbance events regularly affect Tennessee forests. Between 1999 and 2004 approximately 334,000 acres of forestland were disturbed annually. In general, insects are responsible for the majority of disturbance to forests, followed by weather, animals, and humans. Wildfires are responsible for only a limited amount of the disturbance to Tennessee forests. Most insect-related disturbance events occur in the eastern part of the State, while weather-related disturbance events (for example, windstorms and tornados) occur mainly in the Cumberland Plateau region. The southern pine beetle is responsible for much of the insect-related disturbance to Tennessee forestlands. The most recent southern pine beetle epidemic occurred between 1999 and 2002 and damaged approximately 350,000 acres of pine timber in the State with an estimated value of roughly $350 million (Oswalt et al., 2009).

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[11] Changes in the abundance of forest types are primarily due to a southern pine beetle epidemic between 1999 and 2002.

5.2 Literature Review

This section examines recent studies to assess the potential effects of climate change on forest resources. To the greatest extent possible, the literature review focuses on the effects of climate change on forests in the southeastern United States, specifically forests in the TVA region. For a broader discussion of the effects of climate change on forests, see Joyce et al. (2001), Saxe et al. (2001), Shugart et al. (2003), and Birdsey et al (2008).

Several general, overarching conclusions on the effects of climate change on forest resources in general, and in the southeastern United States in particular, can be drawn from the literature reviewed. These conclusions are presented below and discussed in more detail throughout this section.

- All future climate scenarios reviewed predict increases in temperature and either increases or decreases in precipitation associated with increased future CO_2 concentrations. Under climate scenarios that predict increases in temperature and precipitation, forests in the southeastern United States are expected to benefit from increased growth and the range expansion of local species. Under climate scenarios that predict increases in temperature, but decreases in precipitation, a variety of detrimental effects are predicted for southeastern forests, including reduced forest growth, decreased forest area, changes in species composition, and increases in disturbance events. These negative effects are not expected for northern forests where almost all climate scenarios predict increases in forest growth and productivity.
- Due to the uncertainty of the effects of climate change on southern forests and the relative importance of the forest products industry in the southern U.S., forests in the South are considered to be more sensitive to the effects of climate change than forests in most other regions of the country.
- In unmanaged ecosystems, which characterize most of the Tennessee forest resources, the effects of climate change on forests will be limited by the biological properties of individual tree species such as life span, resistance to disturbance, and dispersal limitations. For example, changes in forest composition due to climate change may be delayed if existing trees do not perish for a long period of time or if more suitable species are unable to disperse to gaps in forests. In managed ecosystems, the effects of climate change will be limited primarily by the benefits and costs of adaptation.
- Changes in disturbance events such as wildfires and droughts caused by climate change may be the ecological driver causing significant changes in forest resources in the future. Specifically, the increased occurrence and severity of disturbance events may offset any changes in forest resources caused directly by changes in temperature, precipitation, or CO_2 concentration. Further, altered disturbance regimes may create the conditions necessary for climate-induced changes in forest composition and distribution to occur.
- Forest management may significantly affect how climate change alters forest resources. For example, forest management strategies may be altered to limit the effects of climate change on forest ecosystems, limiting the effects of increased disturbance events. Alternatively, forest management strategies may be altered to encourage the effects of climate change on

forest resources. For example, it may be desirable to create habitats suitable for the northern expansion of southern tree species.

- The northern expansion of many tree species and the growth increases that are predicted to occur in northern latitudes as a result of climate change may lead to a northern shift in forest production and revenue. Tennessee could benefit from this northern shift due to a potential expansion of softwood resources; however, these changes are likely to occur over a 50 to 100 year period, rather than in the near-term.

Each of these key findings is described in more detail in this section. The remainder of this section reviews the direct and indirect biophysical effects of climate change on forest ecosystems, forest management adaptations to climate change, and the effects of climate change on timber markets.

5.2.1 Biophysical Effects of Climate Change on Forests

Forest ecosystems are affected by climate in a variety of ways. As stated in Barnes et al. (1980): "Acting on specific physiological mechanisms of organisms, climate is a major factor [in forests] determining genetic differentiation and speciation, species distributions, competition, disturbance regimes, and growth rates and carbon balance." This section reviews studies on the individual and combined effects of changes in temperature, precipitation, and CO_2 concentration on forest growth, composition, and distribution. Studies on the effects of climate change on disturbance regimes and the implications of altered disturbance regimes on forest ecosystems are also discussed.

5.2.1.1 Effects of Changes in Temperature and Precipitation

Changes in temperature and precipitation are part of broader changes in climate. Thus, changes in temperature may be accompanied by changes in precipitation patterns. More importantly, the effects of altered temperature and precipitation on forest ecosystems are closely related. Most studies consider the effects of either changes in temperature (Bruhn et al., 2000; Saxe et al., 2001; Danby and Hik, 2007) or altered precipitation patterns (McNulty et al., 1996; Hanson et al., 2001), not the combined effects of both. Consistent with the literature, this review discusses the potential effects of changes in temperature and precipitation separately. However, due to the close relationship between temperature and precipitation, the potential effects of changes in temperature and precipitation on forest resources should be considered together.

- **Changes in temperature:** In general, if temperatures increase beyond the optimal species-specific temperature for photosynthesis, negative effects to net photosynthesis and tree growth are likely to result (Barnes et al., 1980). Saxe et al. (2001) note that warming will likely only reduce photosynthesis in areas where temperatures are already optimal for tree growth. A number of studies, including Bruhn et al. (2000) and Danby and Hik (2007), report increases in growth caused by elevated temperatures in cold-limited species (that is, species near the northern edge of their latitudinal range or the upper limit of their elevational range). Saxe et al. (2001) and Birdsey et al. (2008) report that the majority of studies on the effects of temperature on tree growth conclude that moderate increases in temperature will increase tree growth in the United States.

- Increased temperatures may also extend the growing period for trees (Saxe et al., 2001). Specifically, leaf burst may occur earlier in the spring, while leaf senescence and bud hardening may occur later in the fall. However, Saxe et al. (2001) note that gains in tree growth related to prolonged growing seasons will depend on an individual tree's or tree species' ability to achieve an optimal balance between utilizing the full growing season and limiting frost damage caused by improper timing of leaf burst and senescence.
- **Changes in precipitation:** In trees and other terrestrial plants, photosynthesis is affected by both humidity and water availability (Barnes et al., 1980). Specifically, at low humidity and water availability levels, photosynthesis is reduced as trees close their stomata to limit water losses through transpiration, thereby limiting CO_2 uptake. Increased precipitation raises humidity levels and may increase water availability, which allow for increased photosynthesis and tree growth.

Hanson et al. (2001) found that tree growth in the Walker Branch Watershed in Tennessee varied depending on precipitation and soil water availability between years during a six-year study. Specifically, tree growth was two to three times greater in wet years than dry years. However, increased precipitation over long periods of time (that is, multiple years) did not result in significantly elevated growth rates indicating that year to year changes in water availability may affect forest growth rates more than long-term changes in water availability. McNulty et al. (1996) found that annual basal area growth in loblolly pine stands in the Southeast was directly related to precipitation levels. Further, precipitation showed the greatest correlation with annual basal area growth when various physiological factors and changes in temperature were considered in addition to changes in precipitation.

5.2.1.2 CO_2 Fertilization

During photosynthesis, trees use atmospheric CO_2 in combination with water molecules and energy derived from light to generate glucose, which is utilized to carry out a variety of plant processes including growth (Barnes et al., 1980). Thus, changing atmospheric CO_2 concentrations may affect both photosynthesis and tree growth. In general, forest canopy photosynthesis increases as atmospheric CO_2 concentrations increase (Birdsey et al., 2008). However, increases in photosynthesis due to elevated CO_2 concentrations appear to be limited by biochemical regulation; light, nutrient, and water availability; and other climate change factors (Cramer et al., 2001; Norby et al., 2005; McCarthy et al., 2006a; Oren et al., 2001; Shugart et al., 2003; Hanson et al., 2005).

Cramer et al. (2001) projected a global carbon sink over the next century due to increased ecosystem productivity stemming from elevated CO_2 concentrations. However, the projected carbon sink begins to level off starting in 2030 due to the "diminishing return" of the physiological effects of elevated CO_2. Further, the projected carbon sink was reduced when other climatic factors (for example, increases in temperature and decreases in precipitation) were included in climate simulations.

In terms of the effects of light availability on carbon assimilation and net primary production (NPP), Norby et al. (2005) found that in four free-air CO_2 enrichment experiments in North Carolina, NPP increased with increasing CO_2 concentration across four forest stands of varying age, type, and composition.[12,13] When leaf area index was low (that is, before light was a limiting factor in photosynthesis), increases in NPP were caused by increases in leaf area index.[14] However, when leaf area index was high (that is, light availability limited photosynthesis), increases in NPP were caused by increased light-use efficiency. Similarly, McCarthy et al. (2006a) found that following canopy closure, increases in NPP due to increased CO_2 concentrations were directly related to leaf area duration not to overall leaf area.[15]

In terms of the effects of nutrient availability on NPP, Oren et al. (2001) found that increases in tree biomass varied depending on site quality. Specifically, gains in biomass due to elevated CO_2 levels were reduced on poor nutrient-quality sites when compared to biomass gains on moderate- to high-nutrient quality sites. Further, McCarthy (2006) reported that leaf area duration may be regulated, in part, by nitrogen availability. Shugart et al. (2003) reported that increased growth in plants due to increased CO_2 concentrations decreases overtime due to competition for both light and nutrients.

Finally, increased leaf area index, which accompanies increased NPP due to elevated CO_2 concentrations, leads to increased transpiration and reduces water availability (Saxe et al., 2001). Thus, trees may not be able to take advantage of increased CO_2 levels due to the need to limit water loss through transpiration. Although increased atmospheric CO_2 concentrations increase water-use efficiency (more CO_2 molecules enter leaves than water molecules exit when stomata are open), improvements in water-use efficiency may be offset by the maintenance of heat balance in trees, which is regulated through transpiration (Shugart et al., 2003). In particular, trees may need to increase transpiration to maintain heat balance following the increases in temperature that are expected to accompany increased atmospheric CO_2 concentrations.

5.2.1.3 Combined Effects of Changes in Climate (Temperature, Precipitation, CO_2 Concentration)

A number of studies address the combined effects of multiple climate change factors. The majority of these studies focus on changes in forest cover and the distribution of individual tree species and forest types (VEMAP Members, 1995; McNulty et al., 1997; Aber et al., 2001; Hansen et al., 2001; Iverson and Prasad, 2001; Iverson and Prasad, 2002; Iverson et al., 2004; Iverson et al., 2005, McKenney et al., 2007; TWRA, unpublished). However, some studies also address the effects of different climate change scenarios on forest growth (Aber et al., 2001; Hanson et al., 2005; Boisvenue and Running, 2006). Both types of studies are discussed in this section.

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[12] In free-air CO_2 enrichment (FACE) experiments, ambient CO_2 levels in the canopy of experimental stands are manually elevated using a ring of CO_2 sprayers emitting vaporized CO_2 and a central computer control system, which adjusts to varying wind directions and speeds to maintain a constant, elevated ambient CO_2 concentration.

[13] Net primary production (NPP) = (gross primary production) - (total plant respiration).

[14] Leaf area index = the area of leaves displayed over a unit of ground surface.

[15] Leaf area duration = leaf area index per unit of time.

Boisvenue and Running (2006) report that, in general, climate change to date has had a positive effect on forest productivity when water is not limiting. Specifically, Boisvenue and Running (2006) reviewed 49 papers on the effects of climate change on forest growth and found that the majority of papers (37) report positive growth trends due to climate change, while only five papers report negative growth trends due to climate change. Aber et al. (2001) report minor (~2 percent) increases in total forest area and total carbon storage and significant (~20 percent) increases in forest NPP due to climate change based on an analysis using three biogeography and three biochemistry models coupled with three general circulation models (GCMs), which present a range of increases in temperature and precipitation associated with a doubling of current atmospheric CO_2 levels. Hanson et al. (2005) modeled the effects of increased CO_2, ozone, temperature, and winter precipitation on upland-oak vegetation in eastern deciduous forests in the United States. They found that when physiological adjustments to climate change based on field studies were incorporated into their model, increases in CO_2, ozone, temperature, and winter precipitation increased stand biomass in upland-oak forests by 11 percent.

In general, studies on the effects of climate change on species and forest type distributions predict that the distribution of individual species and forest types will shift northward in latitude and upward in elevation (Birdsey et al., 2008). The results of several studies on changes in forest distribution due to climate change are described in Table 5-3, focusing on changes to southeastern species and forest types.

Table 5-3
Studies on the combined effects of changes in temperature, precipitation, and CO_2 concentration on forest distribution

STUDY	MODELS APPLIED	CHANGES IN TEMPERATURE	CHANGES IN PRECIPITATION	CHANGES IN CO_2 CONCENTRATION	STUDY AREA	RESULTS
VEMAP Members (1995)	Three biogeography models (BIOME2, [DOLY]5, MAPPS), three biogeochemistry models (BIOME-BGC, CENTURY, TEM), combined with three general circulation models (GCMs)	+3.0ºC to +6.7ºC change in average annual temperature	+4% to +21% change in average annual precipitation	2 x [Ambient CO_2 concentration]	Coterminous United States	Simulations indicate that forest types of the eastern United States will shift northward. The temperate deciduous forests that make up much of the southeastern United States will be replaced by temperate/subtropical mixed forests with a higher softwood component. Further, depending on the GCM applied, the models predict varying levels of expansion in grasslands and shrublands in the Southeast. The largest expansions of grasslands and shrublands are predicted for climate scenarios projecting large increases in temperature combined with only moderate increases in precipitation.
McNulty et al. (1997)	PNET-IIS – a monthly time-step forest process model and two general circulation models (GCMs)	+3.2ºC to +7.2ºC change in average monthly temperature	-24% to +31% change in monthly precipitation and -1% to +3% change in annual precipitation	2 x [Ambient CO_2 concentration]	Southern United States	Depending on the geographic location of stands and the GCM applied, evapotranspiration rates and soil water stress will be too high to support the leaf areas required for healthy loblolly pine stands. This is similar to the results of Urban and Shugart (1989) who used the ZELIG model to predict that future climatic conditions would no longer support loblolly pine stands. Rather, loblolly pine would be replaced by other, more heat-tolerant pine species, such as, longleaf pine, pond pine, and slash pine. Further, Urban and Shugart (1989) predicted that the health of new pine stands might be diminished by an inability to form a closed canopy due to heat stress caused by increased temperatures.

Table 5-3 (continued)
Studies on the combined effects of changes in temperature, precipitation, and CO_2 concentration on forest distribution

STUDY	MODELS APPLIED	CHANGES IN TEMPERATURE	CHANGES IN PRECIPITATION	CHANGES IN CO_2 CONCENTRATION	STUDY AREA	RESULTS
Aber et al. (2001)	Two transient GCMs (the Canadian Global Coupled Model [CGCM1] and the HADCM2SUL model developed by the Hadley Centre for Climate Prediction) coupled with two dynamic general vegetation models (MC1 and LPJ)	+3.3ºC (Hadley scenario) to +5.8ºC (Canadian scenario) change in mean annual temperature	+17% (Canadian scenario) to +23% (Hadley scenario) change in mean annual precipitation	2 x [Ambient CO_2 concentration]	Coterminous United States	Applying the results of the Canadian GCM, which predicts increased temperatures and decreased precipitation through 2034 and increased temperature and precipitation from 2035 to 2099, predicts conversion of significant portions of southeastern forests to grassland and savanna-woodland by 2030 with reversion to forested areas by 2095. Further, utilizing the Canadian GCM, a significant northward expansion of the Southeast mixed forest type is predicted to replace much of the temperate deciduous forest type that currently dominates all but the southern-most forested areas in the Southeast. Applying the results of the Hadley climate change model, which predicts increased temperature and precipitation through 2099, neither the conversion of forestlands to grasslands nor the expansion of the Southeast mixed forest type are predicted. These results imply that the combination of increased temperatures and decreased precipitation may have significant effects on the distribution of forests in the Southeast.
Hansen et al. (2001)	Seven GCMs in conjunction with the MAPPS biogeography model	+2.8ºC to +6.6ºC change in mean annual temperature	+2.1% to +30.7% change in mean annual precipitation	2 x [Ambient CO_2 concentration]	Coterminous United States	Average results across the different climate scenarios indicate that forested areas will decrease by 11 percent with a range of plus 23 percent to minus 45 percent. The model predicts increases in forested areas under the coolest GCM scenarios and the most significant decreases in forested areas under the hottest GCM scenarios. Under all climate scenarios, southeastern mixed forests are predicted to increase in range due to northern expansion. However, under the hotter GCM climate scenarios, forestland in the Southeast is predicted to convert to savannas and grasslands following the northern migration of southeastern forests.
Iverson and Prasad (2001)	Five GCMs coupled with the DISTRIB model - a regression tree analysis	+0.9ºC to +8.2ºC change in January temperature	-44 mm to +242 mm change in annual precipitation	2 x [Ambient CO_2 concentration]	Eastern United States	For each of the five GCM climate scenarios, reductions in loblolly-shortleaf pine and longleaf-slash pine forests in the Southern U.S. are predicted to occur by the end of the next century using the DISTRIB model. The reductions in the pine forest types coincide with increases in oak-hickory and oak-pine forests caused mainly by a large increase in the range of post oak.

Table 5-3 (continued)
Studies on the combined effects of changes in temperature, precipitation, and CO_2 concentration on forest distribution

STUDY	MODELS APPLIED	CHANGES IN TEMPERATURE	CHANGES IN PRECIPITATION	CHANGES IN CO_2 CONCENTRATION	STUDY AREA	RESULTS
Iverson and Prasad (2002)	Five GCMs coupled with the DISTRIB model - a regression tree analysis	+0.9ºC to +8.2ºC change in January temperature	-44 mm to +242 mm change in annual precipitation	2 x [Ambient CO_2 concentration]	Eastern United States	Found that potential habitats for many southern species, including seven species of oak, loblolly pine, and longleaf pine would increase under potential future climatic conditions due to northward expansion. In general, climate scenarios including large increases in temperature accompanied by relatively small increases in precipitation, leading to high potential evapotranspiration levels, appeared to cause the greatest change in suitable habitat for species.
McKenney et al. (2007)	Three GCMs in conjunction with ANUCLIM – climate envelope software	Not listed	Not listed	A2 Scenario = higher human population, greater pollution, and increased CO_2 concentrations; B2 Scenario = acceleration of energy and resource conservation efforts leading to a decline in CO_2 concentrations by the middle of the next century	United States (excluding Hawaii) and Canada	On average, predict that the center of the climatic niche for tree species in North America will shift northward in latitude by 3.0 to 6.4 degrees depending on dispersal rates. Under both emission scenarios, predict that climatic conditions in the southern United States will be outside of the current known climatic tolerances of the 130 species included in the study by the end of the century.
Dale et al. (2009)	Three GCMs (wet, middle, dry) run by the National Center for Atmospheric Research combined with LINKAGES – a forest stand model, which predicts changes in forest composition and structure, and LSCAP – a landscape model, which predicts changes in land-cover types	Temperature is predicted to increase for all future climate scenarios with the dry scenario exhibiting the greatest increase in temperature Specific increases in temperature not provided	Precipitation is predicted to increase under the wet scenario and decrease under the middle and dry scenarios Specific changes in precipitation not provided	CO2 levels are predicted to increase to 850 ppm by 2100 according to the IPCC A1B scenario under which future energy sources are balanced between fossil-intensive and non-fossil energy sources	The Cumberland Plateau and Mountains of Tennessee and Kentucky	Forest cover is predicted to decrease across all forest types under all future climate scenarios. Reductions in forest cover are predicted to be greater in the Cumberland Mountains than on the Cumberland Plateau. Relative to other forest types in the mountains, mesic deciduous, mixed, and evergreen forests are predicted to incur the greatest reductions in area. Given the predominance of hemlock in mesic mixed and evergreen forests, the distribution of hemlock in the Cumberland Mountains and Plateau is expected to decrease under future climate scenarios.

STUDY	MODELS APPLIED	CHANGES IN TEMPERATURE	CHANGES IN PRECIPITATION	CHANGES IN CO_2 CONCENTRATION	STUDY AREA	RESULTS
TWRA (unpublished)	Average of three GCMs coupled with Random Forests – a predictive data mining tool	Not listed	Not listed	High Scenario: little conservation efforts to mitigate CO_2 emissions; Low Scenario: low carbon emissions due to significant conservation effort	Tennessee	The projections of the distribution of future forest types indicate that there will be large increases in the extent of oak/pine forests in Tennessee by 2100 accompanied by large reductions in elm/ash/cottonwood forests and minor reductions in oak/hickory forests (the dominant forest type in the State). In particular, oak/pine forests are projected to increase in the eastern portions of the State. Further, projections indicate the loss of loblolly/shortleaf pine forests and maple/beech/birch forests in Tennessee by 2100. The specific changes in the distributions of different forest types depend on the climate change scenario applied.

Table 5-3 (continued)
Studies on the combined effects of changes in temperature, precipitation, and CO_2 concentration on forest distribution

STUDY	MODELS APPLIED	CHANGES IN TEMPERATURE	CHANGES IN PRECIPITATION	CHANGES IN CO_2 CONCENTRATION	STUDY AREA	RESULTS

Notes:

1.) Studies do not define ambient CO_2 concentration. We assume that, in most cases, ambient CO_2 concentration refers to pre-industrial CO_2 concentration (approximately 280 ppm as defined in: IPCC WG1 2007).

2.) The timeframe for all studies, except VEMAP Members (1995), is the present-day through the next century.

3.) The VEMAP Members (1995) modeled the effects of climate change for equilibrium conditions (that is, when annual ecosystem NPP equals annual ecosystem decomposition rates). Thus, there is no time component to their projections. The changes in forest type predicted by the different models may occur at any time in the future.

One potential limitation to changes in the distribution of species and forest types caused by climate change is the inability of species to disperse to newly-created suitable habitat (Iverson et al., 2004). If species are not able to disperse into new habitats, there may be no changes to current forest compositions or there may be reductions in forested areas as forest gaps caused by climate change are not filled by new species better suited to local climatic conditions. Iverson et al. (2004) analyzed the potential northward expansion of persimmon, sweetgum, sourwood, loblolly pine, and southern red oak, and found that there is a relatively high probability of migration within 10 to 20 kilometers of current species' range boundaries within the next 100 years. However, the probability of dispersal beyond 20 kilometers in the next 100 years is much less. Further, Iverson et al. (2005) found that there is a lag between the creation of new habitat for tree species and the colonization of the habitat by the species through purely natural processes. Specifically, Iverson et al. (2005) found that in the next 100 years, less than five percent of newly created habitat for the five southern tree species analyzed by Iverson et al. (2004) has a probability greater than or equal to 0.20 of being colonized by one of the five species.

The dispersal of tree species into newly created suitable habitat may be assisted by the presence of disturbed areas (Flannigan et al., 2000) or through changes to forest management strategies (Sohngen and Mendelsohn, 1998). Both disturbance regimes and forest management strategies may be affected by climate change and are discussed in more detail below.

5.2.1.4 Effects of Climate Change on Disturbance Events

Increases in the frequency and severity of disturbance events and the resultant effects may be directly related to climate change (for example, increased temperatures and decreased precipitation may lead to more frequent droughts) or indirectly related to climate change (for example, increased temperatures and decreased precipitation may lead to drier forest conditions, which in turn may increase the risk of wildfires).

One important distinction between many of the indirect disturbance effects discussed here and the direct temperature, precipitation, and CO_2 effects discussed above is that indirect disturbance effects often have more important implications for the current stock of forests than the direct effects of climate change. For example, disturbances, such as fire or insect outbreaks, can eliminate or substantially reduce large stocks of merchantable, or visible, forests, while temperature or precipitation induced growth effects more slowly influence forest structure and function. In general, if disturbances are expected to become more widespread over a region as a result of climate change, they may offset the growth gains caused by temperature, precipitation and CO_2 fertilization. It is thus vitally important to carefully consider the potential implications of the indirect disturbance effects.

Disturbance events may reduce leaf function, deform tree structure, cause tree mortality, alter regeneration patterns and forest succession, disrupt the physical environment, and increase landscape heterogeneity (Dale et al., 2000). When the natural frequency and severity of disturbance events are altered, there may be significant impacts to forest structure and function. Currently, forests may be affected by a number of disturbance events, including fire, drought, insect and pathogen outbreaks, introduced species, hurricanes, windstorms, and ice storms. The changes to these disturbance events caused by climate change and their potential effects on forest ecosystems are discussed below.

- **Fire:** Flannigan et al. (2000) report that the seasonal severity rating (a measure of forest fire danger) will increase by 10 to 20 percent within the next 50 years due to warmer and drier conditions predicted using two transient GCMs. In the Southeast, Flannigan et al. (2000) predict increases in the seasonal severity rating of up to 30 percent using the drier of the two future climate scenarios. Further, Flannigan et al. (2000) predict increases of 25 to 50 percent in the amount of area burned in the United States by wildfires with the majority of additional burn areas located in Alaska and the Southeast. Increases in fire severity and area burned are due to both an increase in the number of low humidity days and the lengthening of the fire season (Birdsey et al., 2008). Fires are typically the result of extreme weather events; thus, increases in the frequency and severity of droughts and lightening storms may be indicative of increased wildfires (Bachelet et al., 2004).
- Lenihan et al. (1998) predict that the amount of biomass consumed by wildfires will increase under warmer climatic conditions. Similarly, Bachelet et al. (2004) predict that the Southeast will become a significant carbon source over the next century with a large portion of carbon loss stemming from an increase in the amount of forest biomass consumed by wildfire due to drier conditions. In general, the northern expansion of southern species would be enhanced by an increase in disturbed areas caused by wildfires (Flannigan et al., 2000).
- **Drought:** For the most part, droughts in the Southeast are random and tend to occur late in the growing season (Hanson and Weltzin, 2000). The seasonality, intensity, and duration of droughts are difficult to predict using current numerical weather prediction models; however, Nielson and Drapek (1998) predict that increases in evapotranspiration due to future climate change will increase drought stress in the Southeast using the MAPPS biogeography model coupled with transient GCMs. In general, forests located on relatively shallow soils or soils with low water availability are considered more susceptible to drought effects (Hanson and Weltzin, 2000). Further, large, mature trees are more resilient to droughts than young, developing trees due to deep rooting systems and substantial carbohydrate and nutrient reserves. The resiliency of large, mature trees to the effects of drought may limit drought-induced dieback, thereby limiting the potential for the migration of new tree species better adapted to altered climatic conditions.
- **Insect/pathogen outbreaks:** Climate change could change the frequency and severity of insect/pathogen outbreaks by altering the development and survival rates of insects/pathogens; modifying tree defenses against insects/pathogens; and altering the abundance of natural enemies, mutualists, and competitors to insects/pathogens (Ayres and Lombardero, 2000). Temperature is the main climatic factor affecting the distribution and abundance of herbivorous insects (Bale et al., 2002). Specifically, temperature increases winter survival of insects, thereby increasing their abundance. However, temperature increases that result in decreased winter snow levels may decrease insect abundance (Ayres and Lombardero, 2000). Gan (2004) found that warmer winters and springs will increase the risk of outbreaks from southern pine beetles, while increases in summer and fall temperatures will have mixed or negative impacts on the risk of an outbreak. Further, Ungerer et al. (1999) predicted that an increase in the minimum annual temperature of 3ºC could increase the range of the southern pine beetle 170 kilometers northward. Changes in precipitation do not appear to have a significant impact on the abundance or distribution of the southern pine

beetle (Gan, 2004). However, a doubling of current atmospheric CO_2 concentrations could increase the risk of a southern pine beetle infestation by 2.5 to 5 times.

- **Introduced species:** The greatest effect of climate change on introduced or nonnative species is the potential expansion of species' ranges (Simberloff, 2000). Frequently, nonnative species have high dispersal rates and are strong competitors, traits that allow them to dominate areas quickly if given the opportunity. Thus, as climatic conditions change, non-native species may be better adapted to establish newly created suitable habitat than native species. Further, non-native species frequently excel in heavily disturbed environments (Joyce et al., 2001). Thus, if climate change increased the frequency of disturbance events, non-native species might increase in abundance.
- **Hurricanes/windstorms/ice storms:** Future climate change may cause increased evapotranspiration leading to an accelerated hydrologic cycle under which more water vapor is transported to higher latitudes resulting in the increased frequency and severity of hurricanes (Dale et al., 2001). McNulty (2002) found that the occurrence of hurricanes may have significant effects on future carbon storage in forests. Specifically, hurricanes may lead to an increase in dead and downed forest biomass, which will increase atmospheric carbon as it decays.

Peterson (2000) reports that, despite a direct relationship between tornado occurrence and temperature, there is not enough information on the formation of tornadoes to predict how climate change will affect the frequency or severity of future windstorms.

Finally, McCarthy et al. (2006b) found that southern pine plantations subjected to increased levels of CO_2 were less vulnerable to damage caused by ice storms (that is, stands suffered lesser reductions in biomass) than southern pine plantations growing under normal conditions. This result suggests that southern forests may be more resilient to the effects of ice storms under future climate scenarios. However, da Silva et al. (2006) report that increased sea surface temperatures caused by global warming may increase the frequency of future ice storms in the Southeast, which may counteract the reductions in stand vulnerability to ice storms. Irland (2000), on the other hand, notes that the effects of climate change on the frequency and severity of future ice storms is unknown.

5.2.2 Human Response and Adaptation to Climate Change

Foresters have a long history of managing forested ecosystems in order to produce flows of timber, water, wildlife habitat, and other benefits. There is widespread recognition that forest management strategies will have to change in order to adapt to climate change, although the rate at which these changes will occur is not yet fully understood (see Joyce et al., 1995; Sohngen and Mendelsohn, 1998; Sohngen et al., 2001; Joyce, 2007). This section reviews literature on potential changes to forest management strategies to adapt to climate change.

As described above, the key ecological effects that will affect forests in the TVA region relate to (a) changes in growth rates, (b) shifts in species composition, and (c) changes in the rate/area of dieback caused by disturbance (bug infestations or fires). Without human adaptation and management, changes in growth rates and shifts in species composition will only have implications over longer periods of time, potentially 30-70 years from the present. Land managers, however, are expected to adapt to climate change in order to take advantage of improved growth rates in some species by reducing rotation ages and planting the species that grow the quickest. While human adaptation will increase the speed at which the forest structure can be adjusted to climate change, changes in growth rates and species composition will still have their strongest implications in the 20-40 year time period, and not in the next 10-20 years. If changes in dieback and disturbance regimes occur, however, they will begin to have impacts in forests immediately. While dieback and disturbance can act fairly quickly to kill large areas of standing forest stocks, the implications of dieback and disturbance will be long-lasting. For example, under natural conditions it will take time for new stocks to grow, particularly if the climate conditions have changed to favor species with seeds that do not exist in the area of dieback initially. Even if humans manage the process and replant species that are optimal for the future climate, it will take many years for the new forest to grow.

It is useful to consider the wide range of potential adaptations that land managers may undertake in response to the impacts of climate change. Changes in growth rates for example may spur landowners to shift towards species that are favored by climate change (for example, planting disturbance-tolerant species, reducing tree densities, and selectively thinning trees most susceptible to disturbance), to replant forests at different spacing, to manage competing species more intensively at the stand initiation stage, or to thin competitors later. Some landowners may even move towards more substantive use of irrigation in drought prone areas. Thinning and prescribed fire may also be used to control potentially large-scale fire impacts, and timber that is damaged by disturbance (fires, pest outbreaks, etc.) will be salvaged. Some responses, such as planting new species or harvesting earlier than anticipated to prevent future losses from forest fires will require anticipation and some degree of confidence in the predictions of climate scenarios, while other responses, like salvaging after disturbances or thinning to reduce fire impacts, require little anticipation.

Many of these adaptations have already been considered in the context of current impacts the forest sector has faced. There is ample evidence, for instance, that foresters will readily convert land from one forest type to another in order to increase growth rates or reduce management costs. In the past 40 years, over 12 million hectares of forest in the southern United States have been converted to loblolly pine plantations (Haynes, 2003) because this species is faster growing than competing softwoods in the region and it is less costly to manage than hardwoods. Similar trends have been observed worldwide as foresters shift species from one region to another in order to find those that have the greatest growth rates for the given climate (see, for example, Daigneault et al., 2008).

Many adaptations to large-scale disturbance events have also been studied. For example, Haight et al. (1995) found that the risk of tree damage and stocking reduction from hurricanes may affect stand rotation length in order to maximize the expected present value of stands. Similarly, Reed (1984) found that the risk of wildfires will shorten stand rotation lengths. Shorter rotation lengths are optimal (in terms of maximizing profit) due to increases in the discount rate used during calculations of the net present value of forest stands where there is a high risk of disturbance. In areas where the potential for fire damage is high, frequent prescribed burns may be utilized to prevent vegetation maturation and unanticipated wildfire ignition (Yoder, 2004). Further, shorter rotation lengths may limit the risk of wildfires by limiting the accumulation of coarse woody debris or standing deadwood. In areas where prescribed burns are a viable management technique, mechanical thinning during the early stages of stand development may further limit the risk of wildfires by reducing stem density. Amacher et al. (2005) found that, although reducing rotation lengths limits the risk of wildfires and increases the net present value of stands, if fuel reduction measures are implemented, net present values may increase with longer rotation lengths. Finally, Amacher et al. (2005) found that reducing planting densities limits the risk of wildfires on plantations, especially when combined with fuel reduction measures.

Adaptations such as shifts in species towards faster growing types, reducing rotation length to avoid fire damage, and increasing thinning in order to reduce fuel loads have been considered by many of the large scale economic-ecological analyses that have addressed climate impacts in forest ecosystems. For example, Joyce et al. (1995) indicate that even with climate change, loblolly pine plantations will continue to expand throughout the Southern United States in the next 40 years. Results from the Burkett et al. (2001) and Irland et al. (2001) studies suggest that more southerly hardwoods and softwoods will continue to move northward, and that softwoods will be favored in the South both by ecological and economic (for example, price) conditions. However, that study also illustrates that while impacts will be detected in the period to 2020, the strongest effects will occur between 2020 and 2050.

Sohngen and Mendelsohn (1998; 2001) used the results from VEMAP Members (1995) with a U.S. timber model and showed how adaptation could efficiently be accomplished by speeding up rotation ages, salvaging timber that does die, and shifting towards faster growing species. Their results do indicate there are potentially large shifts in southern species northward and that these shifts are accompanied by dieback of northerly species and displacement with southern species. While the Southeast as a whole turns out to be more vulnerable to climate change than other regions, the vulnerable regions are farther south than the Tennessee Valley.

5.2.3 Effects of Climate Change on Timber Markets

The effects of climate change on forests could have important impacts on timber markets in the TVA region and throughout the United States and the world. For example, changes in forest growth rates ultimately will affect the quantity of timber available for harvest, while changes in disturbance regimes and altered tree distributions will influence what can be harvested and where (see section 5.2.1 for a discussion of the physical and biological effects of climate change on forests). The human response to these impacts, such as planting tree species adapted to new climatic conditions, shortening harvest rotation lengths, and salvage harvesting (see section 5.2.2), mediated by market prices, ultimately will determine the distribution and type of tree cover in the TVA region.

In general, economic models paired with ecological models predict that U.S. and global forest output will increase and timber prices will fall as a result of climate change. This reduction in prices improves outcomes for those who purchase timber products (consumers), while it reduces returns for landowners (Joyce et al., 2001; Irland et al., 2001; Sohngen and Mendelsohn, 2001). Overall, the current suite of studies suggests that gains in consumer benefits outweigh the reductions in producer returns leading to net economic benefits for the entire United States. This result, however, is predicted using models that consider only the United States. Sohngen et al. (2001) conduct a global analysis and find that timber output increases enough in other regions to cause large price reductions. These price reductions are larger than the increased growth rates in U.S. forests, causing welfare in U.S. timber markets to decline.

The economic implications of climate change on timber markets are expected to vary depending on geographic region. The Southeastern United States, which includes many states outside the TVA region, could experience reductions in producer returns due to the relatively large potential reduction in prices nationally (Sohngen and Mendelsohn, 2001). Because the region produces such a large proportion of timber for the national economy, reductions in timber prices have a fairly large impact on producer surplus in the Southeast. In contrast, producer surplus may increase in the Northeast as the region becomes better suited for timber production and growth rates rise.

Existing studies do not allow us to assess the impacts separately for the TVA region. These studies include the TVA region in the Southeast, but in reality the dominant timber species in the TVA region, particularly in Tennessee, are more similar to Northeastern forest types since they are dominated by oak-hickory forests. In the context of the economic studies described above, many parts of the TVA region would respond more similarly to forests in the Northeast than forests in the Southeast. Thus, based on the existing studies, we conclude that timber producers in the TVA region will experience very small to no impacts in the next 10 years; modest, but positive impacts in the next 50 years; and larger positive impacts over the next 100 years.

5.3 Discussion

The literature reviewed suggests that forests in the Southern United States and in particular in the Tennessee Valley will face several challenges presented by climate change in the future. Both the speed at which these challenges unfold and their scope are not entirely clear from the literature, although some general points are emerging. Here we synthesize those general points and illustrate important uncertainties that need to be resolved in the future.

- There is strong evidence that forests are already responding to carbon fertilization and climate change through increased net primary productivity. As a result, in the TVA region, where precipitation is not currently a limiting factor, one would expect continued increases in growth for existing species, particularly hardwoods, over the next 10-30 years.
- Ecological modeling results indicate that forests in the TVA region could be susceptible to fairly large-scale changes in the types of dominant species. Forests in the region are currently dominated by hardwoods, although several ecological studies suggest that climate change could make the TVA region more suitable for southern pine species, such as loblolly pine.
- The timing of shifts in species distributions for the TVA is not entirely clear. Early work in the 1990s by VEMAP Members (1995) involved steady state analysis that was not specific on time periods. More recent analysis by Aber et al. (2001) and Bachelet et al. (2003) use dynamic climate and vegetation models and find that shifts in species in the TVA region will only occur after the middle of this century.
- There is some possibility of significant drying occurring in western Tennessee by 2030, leading to significant drought-induced dieback of forest stocks. Results do indicate that the risks of drought-induced dieback in the TVA region rise beyond 2030, although these results are limited to specific climate change scenarios.

- A large range of management options are available for adaptation to climate change. Economic models have analyzed adaptation to changes in timber growth rates as well as changes in disturbance and species distribution. One result of the existing studies is that markets will speed the natural adaptation process by salvaging after disturbances, replanting species better adapted to a changing climate, and undertaking other management activities (for example, thinning) to reduce the impacts of disturbances.
- Studies have also shown that market signals will continue to promote the expansion of faster growing species where ecological conditions permit. Given the long-term potential for a warmer climate in the TVA region (beyond 2030), there is a strong probability that later in this century, hardwood forests could be replaced, through adaptation, by faster growing loblolly pine stands. To the extent that the studies also suggest substantial drying and loss of forest growth potential in the existing range of loblolly pine plantations, the TVA region could, later in the century, become a more important region for softwood timber production in the United States.
- Economic models project that climate change will lead to more timber production, and lower timber prices globally. In general, producers in the northeastern United States are likely to gain while those in the southeastern United States will likely lose welfare. Current studies suggest that the TVA region, and in particular Tennessee, will experience modest to no impacts in the near term, modest impacts over the next 50 years, and gains over a 100 year period. In all cases, impacts are mitigated by human adaptation, such as planting species suited to new climates and reducing harvest rotation lengths.

Using the results from this analysis, it is possible to consider the implications of the reference case climate scenario on forests in the TVA region. The climate scenario suggests that from 1990 to 2020 there will be a modest temperature increase of 0.8-0.9°C, and a slight decrease to no change in summer precipitation. Higher temperatures with no additional precipitation could be detrimental to forests, although higher CO_2 concentrations can potentially compensate for this effect by increasing water use efficiency. Based on our assessment of the literature, we believe that the reference case climate scenario does raise the risk of additional drought induced dieback or forest fire events in the region, but that there will be zero to a moderate increase in forest growth. It is highly unlikely that species shifts will occur in the next 10 years.

Risks in the reference scenario rise significantly, however, by 2050 due to larger increases in temperature and potential decreases in precipitation. By 2050, the region would be susceptible to forest losses due to dieback, but the scale of these impacts will be moderated by human responses (for example, fire control and other management strategies discussed above). While the existing hardwoods will still be able to survive and grow in the region, by 2050 there will be opportunities under the climate scenario to experiment more broadly with southern loblolly pine species in the region. While there could be some changes in species abundance by 2050 towards softwoods, we do not expect the shift to be dramatic.

All of the results above, of course, must be carefully bracketed by uncertainties. Perhaps the most important uncertainties relate to the potential climate changes themselves. Forests are largely limited by precipitation; given that climate models differ widely in global and regional forecasts of precipitation changes, forest impacts are difficult to determine precisely. Unfortunately, to date we have relatively few scenarios of climate change and ecological change to consider for the TVA region. In order to build a better understanding of the scope of potential impacts in the TVA region, as well as the timing of the impacts, it would be useful to conduct more thorough analysis of climate impacts using modern dynamic vegetation models and down-scaled climate model results for a large range of climate models combined with regionally-specific economic models.

The near-term impacts of climate change do not appear to be substantial for the TVA region. Beyond the 2030-2050 period, however, the existing studies do suggest that stand replacing disturbances could become more prevalent and that species shifts could become more important. However, none of the ecological models have to date accounted for human adaptations that may be undertaken. In fact, economic analysis of adaptations and market adjustments to climate change and ecological analyses have so far been conducted separately. Economic models use ecological inputs, but ecological models do not account for economic drivers. This unfortunately could lead to a vast overstatement of the full set of impacts on forests because the ecological models essentially assume that the land is unmanaged.

As an example, many dynamic vegetation models now drive vegetation impacts with forest fire simulators. These simulators assume that there is no management of forests and that there is no forest fire fighting. Of course, these management activities would be expected to adjust the probability that fires occur in the first place; and even if the fires occur, their impacts will be moderated by humans. Given the important role that fires play in mediating the ecological adjustment to climate change, it will be vitally important to link economic modeling directly to the ecological assessments to build a better picture of potential impacts.

An issue that has not been discussed in this chapter but which will likely have important implications for forests in the United States is the role of mitigation policy. Some policy makers are calling for forests to be used to sequester carbon. Sequestration policy could in fact be fairly substantial and have important implications on the U.S. landscape. Understanding how potential sequestration in the TVA region could unfold may be important for understanding climate change impacts because these sequestration activities will influence future forest structure

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6

POTENTIAL EFFECTS OF CLIMATE CHANGE ON UNMANAGED ECOSYSTEMS

6.0 Introduction

For the purposes of this review, unmanaged ecosystems or ecological resources are defined as natural systems (both terrestrial and aquatic) that occur in the TVA region and exclude managed systems such as agricultural land and plantation forests. The main ecological focus here is on unmanaged ecosystems in their capacity to provide habitat for fish and wildlife populations and communities. Also, only *direct* impacts of climate change were considered. We consider direct effects to be: (a) those in which climate change factors affect organisms directly; an example of this might be rising temperatures directly triggering changes in the phenologies of ecological events, such as bird migration or amphibian breeding seasons; and (b) ecological responses that are mediated through ecosystem structures, processes, and components, for example adverse impacts to lepidopterans affected by climate-induced changes in the distribution or flowering season of their host-plants. However, we exclude anthropogenic indirect effects such as ecological changes caused by altered land management regimes.

Climate is a major determinant of the distribution and abundance of organisms—in many respects it "sets the ecological stage." For example, temperature and its effects on growing seasons, biochemical reactions, timing of reproduction, the life-cycles of pest species, water temperatures, aridity, etc. are responsible for much of the latitudinal and altitudinal zonation of organisms in natural systems. Temperature is also an important trigger in the timing of ecological events such as hibernation, flowering, breeding, and migration seasons. The timing and amount of precipitation is also a major forcing factor in ecological systems (for example, in fish migration and breeding strategies, plant flowering seasons, and the distribution of aquatic and wetland habitats), and atmospheric CO_2 concentrations affect the growth and abundance of vegetation. Also, extreme climatic events are major determinants of the distribution and health of many ecosystems, including forests and coastal habitats. It follows, then, that change in climate of the degree and extent predicted by many general and down-scaled climate models is likely to have major ecological consequences.

Climate change impacts are already being observed in many ecological systems (see reviews in Parmesan and Galbraith, 2004; Parmesan and Yohe, 2003, Root et al., 2003). These already occurring impacts, combined with modeling results, indicate that climate change is likely to have major adverse impacts in the future on North American ecosystems (Peters and Lovejoy, 1992; Bachelet et al., 2001) in the following ways:

Shifting, breakup, loss, and replacement of species and ecological communities. As climate changes, many species that are components of communities will be forced to shift their ranges to follow cooler temperatures either poleward or upward in elevation. In at least some cases, these migrations are likely to result in the breakup of communities as organisms respond to temperature change and migrate at different rates. On regional and national scales, these changes will result in the replacement of existing communities by communities from further south, from lower elevations, or by novel assemblages of species. Some individual species in North America and the United States are already undergoing range shifts (Parmesan and Galbraith, 2004).

Intensified impacts of invasive species and pests. Invasive species benefit from stress on their host ecosystems when they can outcompete native species. It is likely that the stress imposed on ecosystems by climate change will result in increased rates of colonization by invasives. Also, pest species may benefit from climate change by being able to complete their regenerative cycles in shorter periods. The result of these effects could be more frequent pest attacks of greater intensity. If pest attacks resulted in a greater mass of dead vegetation, the result in forests could be an increased intensity and frequency of wildfires, as is already happening with mountain pine beetle in the Rocky Mountains (Kurz et al., 2008). Increased damage by pests and invasives and their link to fire regimes could result in the long-term in habitat shifts (for example, from forests to grasslands or to forest types dominated by fire-tolerant species as discussed in Gan, 2004; Dale et al., 2009; and Joyce et al., 2001).

Extinctions of plants and animals and reduced biodiversity. While some species may be able to adapt to changing climatic conditions, others will be adversely affected. It is likely that one result of this stress will be that current regional and national extinction rates will be increased, resulting in loss in biodiversity. The most vulnerable species within the United States may be those that are currently confined to small, fragmented, cold-adapted, high elevation habitats that may be sensitive to climate change and afford limited or no migration routes to suitable habitats.

Phenological changes. The timing of major ecological events is often triggered or modulated by seasonal temperature change. Changes in timing may already be occurring in the breeding seasons of birds, hibernation seasons of amphibians and mammals, and emergences of butterflies in North America (Brown et al., 1999; Inouye et al., 2000; Dunn and Winkler, 1999).

Changes in ecosystem processes. Ecosystem processes, such as nutrient cycling, decomposition, carbon flow, etc., are fundamentally influenced by climate; and climate change is likely to disrupt at least some of these processes. While these effects are difficult to quantify, some types of changes can—and have been—observed. Increasing temperatures over the past few decades on the North Slope of Alaska have resulted in a summer breakdown of the permanently frozen soil of the Alaskan tundra and increased activity by soil bacteria that decompose plant material. This effect has accelerated the rate at which CO_2 (a breakdown product of the decomposition of the vegetation and also a greenhouse gas) is released to the atmosphere—changing the tundra from a net sink (absorber) to a net emitter of CO_2 (Oechel et al., 1993; Oechel et al., 2000).

Research indicates that many North American ecosystems are already responding to the changing climate, as detailed in Table 6-1.

Table 6-1
Reported climate change-induced ecological changes in North America (adapted from Parmesan and Galbraith, 2004)

Category	region	source
Phenological Changes		
Forbs, birds	Wisconsin	Bradley et al. (1999)
Bird (Mexican jay)	Arizona	Brown et al. (1999)
Bird (tree swallow)	All North America	Dunn and Winkler (1999)
Amphibians	New York	Gibbs and Breisch (2001)
Fish	New England	Juanes et al. (2004)
Distributional/Abundance Changes		
Forest	Florida	Ross et al. (1994)
Shrubs	Alaska	Sturm et al. (2001)
Shrubs, mosses, grasses	Alaska	Chapin et al. (1995)
Birds	Western North America	Johnson (1994)
Mammals	Canada	Hersteinsson and MacDonald (1992)
Insects	California	Crozier (2003)
Insects	California	Parmesan (1996)
Amphibians	Oregon	Kiesecker et al. (2001)
Ecosystem-Level Changes		
Boreal plants	Arctic Canada, Alaska	Lucht et al. (2002) Zhou et al. (2001) Myneni et al. (1997) Keeling et al. (1996)
North American plants	All North America	Hicke et al. (2002)

The remainder of this chapter reviews the literature to assess the extent that the types of changes detailed above are already occurring in the TVA region or have been projected to occur in modeling studies. The literature review encompassed computerized literature searches and personal contacts with climate change and wildlife professionals with knowledge of impacts work in the TVA region, including personnel in U.S. EPA (both the national headquarters in

Washington DC and Region 4), the U.S. Forest Service, state fish and wildlife agencies, and non-governmental organizations.[16]

6.1 Ecological Resources in the TVA Region

Extending from only 250 feet above sea level in the west (the floodplain of the Mississippi River) to over 6,000 feet above sea level in the east (the Great Smoky Mountains), the TVA region supports a wide diversity of terrestrial ecological habitats. These range from riparian forests in the west, through upland oak-hickory and pine-oak forests, to high elevation spruce-fir forests, and shrub-dominated or grassy "balds" in the mountains to the east (CWCS, 2005).

Despite its southern geographical location, the TVA region also supports a diversity of aquatic habitats. Rivers and lakes in the western part of the area are generally warm water systems, supporting fish and invertebrate species that can tolerate higher water temperatures. However, some of the larger lakes and reservoirs in eastern and central Tennessee are deep enough to maintain cold water hypoliminia with cold water species such as rainbow and lake trout (for example, Dale Hollow and Watauga Lakes). Cold water streams exist above about 3,000 feet in the mountainous east of the area; there are approximately 625 miles of cold water streams in the Southern Appalachian Chain in Tennessee and a further 220 miles in the Great Smoky Mountains National Park (GSMNP). These are "wild" streams in that their fish populations are large and robust enough that they do not need to be stocked.[17]

This habitat diversity results in the area being one of the most species-diverse in North America and a center for unusually high levels of endemism. For example, with 325 fish species (more than any other state), greater than 300 species of birds, 90 mammals, 70 amphibians, and more than 2,300 varieties of plants, Tennessee is one of the most diverse states in the United States. This diversity extends beyond the borders of Tennessee: Alabama, Georgia, Mississippi, and North Carolina are all within the top twenty most species-diverse states (Stein, 2002); and Alabama, Georgia, Tennessee and North Carolina are among the 20 states with the highest levels of endemism.

Many plant and wildlife populations in the TVA region are fragmented and at risk from stressors other than climate change. For example, 16 fish species in Tennessee alone are listed by the Federal government as endangered or threatened under the Endangered Species Act, as are 41 species of mussels and 1 crustacean species (FWS, 2009). Because of these high levels of diversity and endemism and the stresses that already affect many species, the potential adverse impacts of climate change on biodiversity in the TVA region must be considered as significant at both a state and a national level.

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[16] Manomet Institute researcher Dr. Hector Galbraith conducted the computerized literature searches using the Wood's Hole Oceanographic Institute Library and the Web of Science and CSA Illumina search engines. Searches were performed for the entire TVA region and for each of the constituent states, with various search terms including climate change, global warming, ecosystems, fish, wildlife, and habitat. Dr. Galbraith also contacted climate change and wildlife professionals who could have knowledge of impacts work in the TVA region to capture grey literature missed in the computer searches.

[17] See www.tennessee.gov/twra/fish/StreamRiver/wildtrout/wildtrout.html for further detail.

6.2 Current and Projected Impacts on TVA Region Ecological Resources

6.2.1 Observed Climate-induced Changes in the TVA REGION

No data or observations were found in either the peer-reviewed or grey literature to indicate that climate change effects were already being recorded in TVA region ecosystems or on their wildlife and habitats. This finding may be a function of lack of data rather than a true lack of effects since impacts are already being observed in many other areas of the United States, as noted in the introductory section of this chapter.

6.2.2 Projected Future Changes in TVA Region Forest Ecosystems

A number of studies have modeled potential impacts of climate change on TVA region forests:[18]

Dale et al. (2009) modeled future changes in forest species and landscapes in the Cumberland forests of Tennessee and Kentucky through 2100. Three general circulation models were used (ccsm[3], PCM, and JAMSTEC, which are approximately "wet," "middle," and "dry" scenarios, respectively). The study used the A1B emission scenario. Forest tree biomass and species changes were modeled using the forest ecosystem model LINKAGES and landscape-level changes using the landscape model LSCAP.

The results of this modeling study project that there will be marked changes in the composition of the mesic deciduous forests of the Cumberland Plateau and Mountains over the next century. Some of these changes will be directly attributable to climate change; projected "increaser" tree species include American basswood and shagbark hickory, while projected "decreasers" include sugar maple and yellow buckeye. Hemlock is also projected to decline in abundance due *indirectly* to climate change as the warming temperatures favor the overwinter survival and spread of hemlock wooly adelgid, a major pest and killer of this tree species. These changes in species representation could be significant for wildlife species dependent on particular tree species.

Dale et al. (2009) also modeled the effects of future land use change on ecosystems on the Cumberland Plateau and in the Cumberland forests. Using the LSCAP landscape model to estimate changes in land-use and land-cover types and based on the assumption that much of the existing larger patches of private forest will be developed for second-homes, Dale et al. (2009) predict that increasing development by humans will also have major impacts on ecosystems. Their results predict that most land cover types will be fragmented and reduced by development, and that the mean patch size of mesic forests will be reduced by 30 percent on the plateau and 77 percent in the mountains. This loss of forest cover and fragmentation will greatly affect the forest ecosystems present in the area. The Dale et al. (2009) results show that the *total* impacts on the forest system may be underestimated using a one-stressor-at-a-time approach.

[18] Note that some of these studies, and others of relevance, are also cited in Chapter 5.

VEMAP (1995). Assuming a doubling of atmospheric CO_2 and using three general circulation models (OSU, GFDL, and UKMO) and three biogeographic models (DOLY, BIOME2, and MAPPSS), VEMAP members modeled projected shifts in major vegetation communities in the contiguous United States. Assuming a doubling of CO_2, the GCM/biogeographic model runs agree in their projections that the temperate deciduous forest that is currently the major biome in the TVA region would be replaced with warm temperate mixed or evergreen forests. Extrapolating from this prediction, it is likely that there will be a transition from oak-hickory forest to an ecosystem with a much higher representation of conifers such as shortleaf and loblolly pines. Such a dramatic change in forest type would have major implications for wildlife habitat.

Iverson et al. (1999) modeled changes in forest distribution in the TVA region under a doubling of CO_2 and using the UKMO general circulation model. Their results differ from those of VEMAP (1995) in that they predict that oak-hickory forest will remain the dominant forest type in the area but that oak-pine forest will spread further south, especially on the Cumberland Plateau. Iverson et al. (1999) also modeled changes in distribution of individual tree species. In accordance with their predicted forest shifts, they project that the southern conifer, loblolly pine, will extend north from its current range to colonize the TVA region and spread as far north as the midwestern states.

Prasad et al, (2007) modeled the response of 134 tree species in the eastern United States to climate change. Their model projects that under a doubling of CO_2 oak-hickory forest will continue to dominate much of the TVA region landscape but that loblolly and shortleaf pine forests will extend their ranges northward to achieve greater representations. These predictions, which match the Iverson et al. (1999) predictions, are based on averaging the results from three GCMs (Hadley 2, PCM, and GFDL). In the Great Smoky Mountains National Park, Prasad et al. (2007) project the loss of high elevation forests dominated by spruce, fir, hemlock, birch and beech and their replacement with oak-hickory forest. Prasad et al. (2007) also project the loss of riparian floodplain forests dominated by elms, ashes, and cottonwoods in the TVA region. However, because riparian floodplain forest is such a local and fragmented habitat type, this result should be treated with some caution.

TWRA (unpublished). The Tennessee Wildlife Resources Agency has recently produced a draft document that projects impacts of climate change on wildlife and their habitat. This work is based on a review of published scientific studies and also draws on some studies that have not yet reached the publication stage. In general, the results of this review are consistent with the results of the studies outlined above:

- Oak-hickory forest will persist in the TVA region under a scenario of a doubling of CO_2, although it will be reduced in area and fragmented by the intrusion of pine-oak forest and loblolly-shortleaf pine forest.
- Bottomland hardwood and conifer forest will be reduced in area by about 40 percent and replaced by oak-hickory.
- Higher elevation “northern” forest types such as spruce-fir and northern hardwoods will be either eliminated from the area or much reduced in extent

- The ecological effects of insect pests and invasive plant species could intensify under climate change. TWRA (unpublished) cites Gan (2004) that the current mortality of pines in the TVA region could be increased by a factor of between 4 and 7.5. This could, potentially, have major effects on stand composition and wildlife habitats.
- Fire can be a major determinant of the structure and composition of forest communities and wildlife habitat (Dale et al., 2001). Under climate change, fires could increase in frequency and intensity, especially if droughts become more frequent or prolonged, as climate models predict. This could have major impacts on forest stand composition and wildlife habitat.

All of the modeling studies cited above generally concur that forest communities and the wildlife habitats that they provide will be affected by climate change and that the magnitudes of the impacts are dependent on forest type. In lower-elevation areas we may expect to see major impacts on floodplain forests as cottonwoods and ash are replaced by oaks and hickories. At middle elevations and on the Cumberland Plateau oak-hickory forest will persist but will be fragmented by the intrusion of pines (loblolly and shortleaf) from further south. At higher elevations in the southern Appalachian Mountains, certain "northern" trees and forest types may be eliminated entirely from the area (eastern hemlock, spruce-fir forest and northern hardwoods forest).

6.2.3 Potential Impacts of Climate Change on Wildlife

While the potential impacts of climate change on forest ecology have been relatively well studied in the TVA region, projecting the modeled changes to their effects on wildlife and their habitats has received little attention. However, it is likely that the changes in forest composition and patch sizes that are projected in the studies cited above could have significant impacts on wildlife and their habitats. At the lowest elevations, the replacement of bottomland hardwood forests by oak and hickory or pines could have major impacts on the distribution and abundance of wildlife species dependent on the floodplain forests, such as white-tailed deer, beaver, and associated aquatic life. At middle elevations, the replacement of oaks and hickories and the mast that they provide for wildlife nutrition by pines could also negatively impact the high diversity of wildlife species that currently inhabit this forest type (for example, white-tailed deer, wild turkey, and vernal pool amphibians and other organisms). At the highest elevations, the loss of hemlock, northern hardwoods, and spruce-fir forest could have major impacts on the wildlife species that are entirely restricted to these habitat types in the TVA region, including rare and restricted high-elevation plant and amphibian species, birds such as saw-whet owls and black-capped chickadees, and mammals such as red squirrels and snowshoe hares. In general, the projected impacts on TVA region forests are likely to result in a significant reduction in wildlife diversity.

Climate change may also affect wildlife populations in ways other than through habitat-mediated impacts. Changes in temperature, precipitation, and seasonality may have direct effects on the phenologies of events, the distribution of organisms, and their demographies. Many of these impacts are already being observed elsewhere in the United States as species shift their migration seasons, breeding seasons, distributions, etc. (see Table 6-1 for examples). As yet, none of these changes have been unequivocally reported for the TVA region; however, such results require detailed long-term studies and the lack of data may be a function of the lack of research effort to date, rather than to the absence of effect. It is conceivable that some of the wildlife species that currently occur in the TVA region could be particularly vulnerable to climate change. These include amphibian and reptile populations since so many of their behavioral and demographic events are driven by climate and high elevation species. Burns et al. (2003) predict that the GSMNP could lose a total of eight high-elevation mammal species, at same time as gaining another 29 species.

6.2.4 Changes in Aquatic Ecosystems

Climate change may, potentially, bring about a number of changes that could impact freshwater ecological resources in the TVA region. These include elevated water temperatures, increased “flashiness” of streams, depleted flow during droughts, lowered oxygen levels, increased evaporation, and the elimination of hypoliminia in larger lakes and reservoirs (TWRA unpublished). All of these changes could affect the physical and chemical habitats of aquatic plants and organisms.

Increased water temperatures due to warming are most likely to impact cold or cool water aquatic species assemblages (EPA, 1995 and 1999). In the TVA region this effect is likely to be manifested in reductions in cool or cold water habitat in the mountainous headwaters and in the larger lakes and reservoirs where cold hypoliminia still exist. Specifically this could mean reductions in habitat for brook and brown trout (the headwaters) and for striped bass (lakes and reservoirs). All of these are popular quarry species for anglers. EPA (1995) modeled the likely effects of a warming climate on fish habitat throughout the United States. For Tennessee and neighboring states the EPA projects that under a doubling of CO_2, the extent of cool water habitat for muskellunge and walleye will be reduced by up to 49 percent, while habitat for the cold water species – brook and brown trout – will be reduced by up to 100 percent. Warm water habitat and the species that it supports will typically expand into areas that were previously cool or cold water areas.

The change from cool or coldwater to warm water habitats could have important consequences for fish diversity in the TVA region and on already imperiled species. Of the 85 fish species of greatest conservation need in Tennessee, 26 percent are dependent on cool or cold headwaters streams and could be at even greater risk from climate change than they currently are (CWCS, 2005).

Other indirect effects of climate change on fish populations could include loss of breeding habitat due to increased deposition of silts during flash floods, resulting in smothering of the eggs of fish that spawn on gravel or sand banks, and habitat being temporarily lost as smaller streams, lakes, and pond dry during drought (TWRA, unpublished).

Freshwater bivalves could also be impacted by increased frequencies and severities of flash floods. These organisms rely on fish to carry their early life stages upstream to suitable rearing habitat. They could be adversely impacted if flashfloods prevented the carrier fish from reaching these upstream areas (TWRA, unpublished).

6.2.5 Implications for Species of Special Concern

As already discussed, the TVA region is unique in North America in the numbers of state or federally listed species of plants and animals that it supports. Many of these species are listed because they already have elevated extinction risks—their habitats are highly fragmented or they are restricted in their distributions (for example, cave-dwelling amphibians, cold-water fish). As yet, the potential impacts of a changing climate on these species have not been evaluated. However, it is likely that climate change could result in their further loss within the area, or they may be eliminated entirely. For example, Corser (2008) has shown that the current distributions of amphibian species on the Cumberland Plateau (many of which are state and/or federally listed as endangered) are a result of changing thermal habitats under long-running cycles of climate change. The implication is that these distributions will likely change further under anthropogenic climate change, with already rare species become even more restricted or eliminated entirely from the area. In the worse cases this could lead to the extinction of species that are already confined entirely to this geographical area. Since so many species that occur in the TVA region are unique to the area, the end result could be a significant increase in extinction risk.

6.3 Summary and Important Information Needs

Research on the potential impacts of climate change on ecological resources in the TVA region has been patchy. While we have a good broad-brush picture of how major forest types may be impacted and we have some data on how cold and cool water streams may be affected, we lack sufficient finer detail about how the biodiversity of the area is likely to be impacted. Of most concern is that we do not have a good understanding of which special concern species are more or less vulnerable to climate change, how the status and distributions of these species might change, how their extinction risks may be changed, which other stressors might interact with the effects of climate change, how we might intervene to ameliorate losses due to climate change, how climate change might affect our future conservation management and planning, or which monitoring schemes we need to initiate to track the effects of climate change on ecological resources. These are all urgent information gaps that remain, as yet, unfilled.

We would suggest that the first step in moving toward answering these questions would be a thorough inter-state vulnerability evaluation. Such evaluations are already being performed in Massachusetts, New Mexico, and Washington. The Massachusetts vulnerability assessment might be most similar to how a TVA ecological evaluation could be structured. The analysis is being developed by the Manomet Center for Conservation Sciences in collaboration with the state Division of Fisheries and Wildlife, with the objective of characterizing the likely vulnerabilities of major habitat types and Species of Greatest Conservation Need to future climate change. This assessment also seeks to develop management plans for the conservation of threatened habitats under climate change and to inform future land acquisition strategies.

The objective of a TVA region vulnerability assessment could include:

- Identifying special concern species that are most vulnerable to climate change, their likely fates over the remainder of this century, and how their extinction risks may be altered.
- Identifying habitats most at risk.

- Projecting habitat trajectories (that is, how they will change) under a changing climate.
- Mapping likely changes in the spatial distributions and extents of habitats and species.

6.4 References

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7
POTENTIAL EFFECTS OF CLIMATE CHANGE ON RECREATION

7.0 Introduction

This chapter reviews literature describing the potential effects of climate change on recreational activities and describes those effects, to the extent possible, in the context of the TVA region. Through changes in temperature, precipitation, and frequency/severity of extreme events, climate change will have both direct and indirect effects on both the supply of and demand for recreation. As humans adapt to these changes, participation in various recreation activities will also change. The U.S. Climate Change Science Program's (CCSP's) report on human welfare (2008) and others have reviewed these effects in detail; the purpose of this literature review is not to replicate this level of detail, but rather to identify the most important conclusions of the literature and how they may be applicable to the TVA context.

This review does not encompass the more general literature on how climate change may affect the broad range of contributors to quality of life (one of which is recreational activity). Several recent studies have reviewed these effects, both in a general context (for example, Center for Integrative Environmental Research, 2007, UN Millennium Assessment, 2005, US Climate Change Science Program Assessment 4.6, Cowie, 2007) and in a more geographically specific context (for example Puget Sound Partnership, 2005).

The literature has concluded that climate change associated with mid-range forecasts from general circulation models will change recreation opportunities and participation patterns across the United States. Specifically:

- Recreational activity in the winter months (for example, cross country skiing) will decline and summer activities (for example, golfing) will increase.
- Rising lake and river temperatures will cause warm water fishing to be substituted for cold water fishing.
- Changes in river runoff will affect reservoir levels, thereby directly affecting reservoir-based recreation.
- Species will migrate to higher altitudes and/or latitudes, affecting wildlife viewing, hunting, fishing, and other activities involving wildlife.
- Overall, recreational activity and its associated value will increase.

Research has not clearly established how recreation would be affected within the TVA region, as this depends both on the effects of climate change on recreation resources and participants' adaptation and substitution decisions, neither of which appears to have been the subject of academic or other research.

7.1 Tennessee Valley Recreation: Characterization and Trends

Water resources, managed forests, and unmanaged ecosystems represent important recreational assets in the TVA region. TVA manages 49 reservoirs and approximately 100 recreation areas within the TVA region (TVA, 2009). In Tennessee alone, there are 54 state parks, 77 state natural areas, and 32 of TVA's reservoirs (TVA, 2008). Over 25 million people visit these sites annually to participate in biking, hiking, hunting, fishing, and boating activities (TDEC, 2009). The Great Smoky Mountains National Park is also located within the Tennessee Valley. The park offers 2,115 miles of streams, 700 miles of which are fishable rivers, 800 miles of hiking trails, and other recreational opportunities (NPS, 2009a and 2009b).

Data on the use of these resources are available from the 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation, published by the U.S. Fish and Wildlife Service in conjunction with the U.S. Department of the Interior and Census Bureau (FWS and Census, 2006). The survey has participation data at both the national and state levels. We present a characterization of Tennessee recreation below. While not a complete picture of the TVA region, it provides a useful frame of reference since the majority of TVA's jurisdiction is within Tennessee.

As displayed in Table 7-1, the most frequent activity reported in Tennessee is wildlife viewing (including feeding and photography). Fishing ranks a close second in terms of activities days but had fewer than half as many participants. Hunting also had substantial participation, but ranks well below fishing and wildlife viewing participation levels both in terms of number of participants and participant days.

Table 7-1
Select activity participation levels in Tennessee

Activity	Number of Participants	Number of Participant Days
Wildlife Viewing	2,362,000	15,486,000
Fishing	871,000	15,103,000
Hunting	329,000	5,729,000
Source: 2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation		

Data on recreation across the TVA region are also available from the recently published National Survey on Recreation and the Environment (NSRE, 2007). The survey provides statistics on participation and trends in recreation for the nation, as well as by state and region. The most recent survey covers the time period from 1999 through 2005. In the survey, recreational opportunities are divided into seven categories:

- Developed-setting land activities

- Nature-based land activities
- Water-based activities
- Viewing/learning activities
- Snow and ice-based activities
- Outdoor sports individual activities
- Outdoor sports team activities

For the purposes of this study, we focus on the first five categories of activities because we did not find literature presenting data specifically related to individual and team outdoor sports. However, while these two categories are not addressed individually, we discuss how specific activities (for example, golf) may be adversely affected by climate change where appropriate.

In the TVA region, many of the most popular activities occur in a developed setting and include walking for pleasure, gardening or landscaping for pleasure, family gatherings, and driving for pleasure. Outside of a developed setting, visiting a wilderness area and day hiking top the list of land-based activities with just over 37 percent of the region's population participating in each activity. A large number of residents also participate in water-based activities. Notably, swimming in lakes or streams and boating each have participation rates exceeding 37 percent. Freshwater fishing and warmwater fishing follow closely behind with 35.5 and 32.5 percent participation, respectively. Outdoor viewing and learning activities also have high participation levels. The most popular activities in this category were viewing and photographing natural scenery, sightseeing, and visiting nature centers with 61, 59, and 55 percent participation rates, respectively. Also of note is that 49 percent of the population participates in viewing and/or photographing wildlife. Given the southerly latitude of the region and predominance of low elevation landscapes, snow and ice-based activities have very low participation rates, with just 15 percent of the population participating in any type of snow or ice activity. The most popular snow-based activity among residents is sledding (14 percent participation rate; NSRE, 2007).

The NSRE study also reports on changes to recreation participation rates by activity between 1995 and 2004. Overall, the study finds that among residents of the TVA region, the number of participants in outdoor recreation increased seven percent. However, participation rates as determined by percent of residents participating in outdoor activities decreased by approximately six percent. Overall, the participation rate for water-based activities decreased slightly (approximately seven percent) while participation in land based activities grew by 16 percent.

Cordell et al.'s (2009) study on recreation trends in the United States finds that nationally, as NSRE reports for the TVA region, the number of people participating in outdoor activities has increased over the past three years. However, the authors caution that future trends in participation in outdoor recreation are hard to predict and will likely be affected by a combination of factors including changes to climate, population, the economy, technology, land development, and culture.

7.2 Literature Review

Since Harold Hotelling's letter to the National Park Service in 1947 describing a way to estimate economic value of visits to national parks, the natural resource economics literature contains many publications on the topic of the non-market benefits of recreation (Trice and Wood, 1958 and Burt and Brewer, 1971 are important early papers in this literature). This literature describes the value of both **consumptive uses** (for example, fishing, hunting) and **non-consumptive uses** (for example, wildlife viewing) of natural resources. Recreation involves site-specific activities and, as such, any values measured for that experience are considered to be **use values**.

BOX 7.1: KEY TERMS WITHIN RECREATION LITERATURE:

Consumptive Use Value: The value placed on natural resources that are directly consumed. In the case of recreation, the value of the entire recreational experience is often considered to be the consumptive use value (that is not just the value of the fish). [1]

Non-consumptive Use Value: The value of environmental resources and services that are not consumed or traded in the market but still provide services. Examples include the hydrological benefits of a watershed, a visit to a national park, bird watching, etc. [1]

Use Value: Use value is the value received from direct use of the resource. [2]

Nonuse Value: Nonuse value (also called passive use value) is the value of a resource independent from people's present use of the resource. Nonuse value is also said to be the intrinsic or existence value of the resource.[2]

Willingness to Pay (WTP): The maximum sum of money an individual will pay for a good.[3]

Contingent Valuation Method (CVM): The contingent valuation method is a stated-preference method for estimating non-market/nonuse resource values. CVM asks people about their willingness to pay for a specific environmental resource or change in environmental amenity. CVM is the only method capable of providing estimates of nonuse values. [3]

Travel Cost Model (TCM): A travel cost model is a demand-based model that infers the value of a recreational resource through the use of information about how much visitors spend getting to the resource.[4]

Random Utility Model (RUM): The random utility model considers the decision to visit a specific site and assumes that the choice was made based on the characteristics of the site. This method attempts to model the tradeoffs between various characteristics of different sites and thereby value the characteristics.

Sources:
1. McNeely, Jeffrey A. (1988). Economics and Biological Diversity: Developing and Using Economics Incentives to Conserve Biological Resources. IUCN, Gland, Switzerland.
2. Tietenberg, Tom. (2006). Environmental and Natural Resource Economics, 7th ed. Pearson, Boston.
3. Freeman, Myrick III. (2003). The Measurement of Environmental and Resource Values, 2nd ed. Resources for the Future, Washington D.C.
4. Parsons, George R. (2003). The Travel Cost Model. In *A Primer on Nonmarket Valuation*. Champ, Patricia A., Kevin J. Boyle and Thomas C. Brown, Eds. Kluwer Academic Publishers.

More recent literature has also indicated that recreational activities are likely to be both directly and indirectly affected by changes in climate (for example, Morris and Walls, 2009). Notably, demand for an activity will be directly affected by changes in temperature, precipitation, and the frequency and severity of extreme weather events. The effects of climate change will also impact recreation demand indirectly by changing the natural resources and amenities upon which an activity depends.

As noted above, the literature does not address climate change impacts on recreation within the specific geography of the Tennessee Valley. Therefore, we use literature we judge to be most applicable to TVA and the TVA region. The literature review follows the spirit of CCSP's "Effects of Global Change on Human Welfare" (CCSP 4.6, 2008, Chapter 4) report by Cropper et al., using a similar structure to cover the following topics: (1) the direct effects of climate change on demand for recreation, (2) the indirect effects of climate change, and (3) the economic effects and modeling.

While we focus primarily on studies relating directly to applicable recreation activities, in some cases we use studies on tourism as another measure of the importance of recreation within the region. Tourism studies in this section act as a valuable addition to the available literature purely focused on recreation activities for two reasons. First, there are several studies that examine both recreation and tourism (see Wall, 1998), as tourism, like recreation, is dependent on climate factors and natural resources and amenities. Second, tourism studies supplement recreation literature by helping link changes in recreational participation to more macro-oriented measures of economic activity within the region. Although similar and complementary, it is important to note that tourism studies rely on a different set of models and metrics (for example secondary effects captured via Input-Output models) as compared to recreation studies, which focus on measures of economic efficiency such as willingness to pay or opportunity costs.

7.2.1 Direct Effects of Climate Change on Demand for Recreation

Given recreation and tourism's dependence on the environment, it is not surprising that demand, participation, and enjoyment of recreational activities will be heavily affected by temperature, precipitation, and climate variability (CCSP 4.6, 2008). Lohman and Kaim (1999) identify five key factors in the decision to travel and participate in recreation: the ability and the motivation to travel influence demand, while the attractiveness, amenities, and accessibility of a recreational site affect substitution decisions. Among the variables that determine the perception of attractiveness, weather conditions are cited as being one of the most important. Michigan State's Pileus Project also includes weather conditions as one of the four most important factors influencing travel decisions (Pileus Project, accessed March 16, 2009).

Below, we present a summary of the potential effects of changing temperature, precipitation, and increased frequency and severity of extreme events on recreation and tourism demand. While these three factors are presented separately, it is important to note that the potential effects cannot be considered in isolation. The impacts on recreation demand of changes in temperature will be affected by changes in precipitation and frequency and severity of extreme events and vice versa.

7.2.1.1 Temperature

Increasing temperatures can have positive or negative impacts on recreation and tourism, depending on the geographic location, the nature of the activity, and the extent of temperature increase. Hall and Highman (2005) report ideal temperature ranges for various water and land activities such as boating, fishing, and golf; their findings suggest that demand for specific activities will increase based on how many days are in these ideal ranges. Several studies show that for selected regions and activities, as temperature levels increase, participation in an activity will also increase (for example Scott and Konopek, 2007). In some instances, this positive effect can be substantial. Scott and Jones (2005) find that in Canada, climate change may lengthen the golf season by up to eight weeks. While the TVA region may not experience such an extension, climate change is likely to extend the golf season.

However, increased temperature does not always correspond to increased recreation participation or enjoyment. Several studies find that use only increases with temperature up to a certain threshold, above which additional temperature increases lead to decreased participation (Saunders and Easley, 2006; Hamilton and Tol, 2006; and Loomis and Richardson, 2006).

7.2.1.2 Precipitation

Changing precipitation patterns will directly affect demand for specific types of recreation by affecting the attractiveness of a recreational opportunity and through changing stream flows. If potential participants believe there will be increased cloud cover due to increased precipitation, the attractiveness of an area may be diminished, and thus participation demand may decrease (Gössling and Hall, 2006). Changes in stream flow also have a significant impact on the suitability of a resource for recreation. Stream flows will be affected by changes to snowpack and snowmelt as well as altered rain patterns. Several studies have shown that the quality of recreation as a function of stream flow varies depending on flow; for each specific stream activity, there is a minimum required flow, optimum flow rate, and maximum level. Demand for recreation such as rafting, kayaking, or fishing decreases as flow deviates from the optimum (Brown et al., 1991 and Daubert and Young, 1981). Changes in precipitation are likely to have an effect on humidity, cloud cover, and fog, which may have positive or negative effects on recreational activities (Dai et al., 2006; IPCC WG1, 2007).

7.2.1.3 Increased Frequency and Severity of Extreme Events

Demand for certain types of recreation will also be affected by increased frequency and severity of extreme events. Lightning, flooding, and tornados will all decrease the demand for recreation by creating situations where participation is not possible. DeFreitas (2005) explains that because recreation is voluntary, it only occurs if conditions meet the needs of the participant.

7.2.2 Indirect Effects of Climate Change on Recreation

Climate change will also indirectly affect recreation and tourism by changing the quality and availability of recreation resources. The direct biophysical changes mentioned in Section 7.2.1 above will have far reaching indirect consequences throughout the recreation industry. As Wall

(1998) explains, the recreation industry's dependence on the environment makes it vulnerable to changing characteristics of surrounding natural resources. CCSP 4.6 (2008) suggests that climate changes could alter the availability or quality of the resources necessary for specific activities (that is, golf, boating, fishing, camping, wildlife viewing, etc.), and thus affect people's willingness to participate in the activity (Kinnell et al., 2002 and MacMillan et al., 2001).

For all these reasons, recreation will be vulnerable to both changes in amenities and changes in patterns of use. As temperature, precipitation, and more extreme weather patterns affect the climate and amenities of certain areas, participants may begin to change their recreational activities and destinations including ceasing recreational activities altogether (Hamilton and Tol, 2004; Kim et al., 2007).

7.2.2.1 Changes to Water Availability and Timing

Water resources provide multiple recreational opportunities that range widely across consumptive and non-consumptive uses and vary across types of water bodies. As precipitation patterns change, all of these water-based activities stand to be affected.

Less winter snow fall and/or increased rain in the spring can lead to high early season runoff which in turn may cause lower summer river flows. These changes may be amplified by reservoirs that were not built to handle heavy early season runoff. If the reservoir cannot hold the high early season runoff, the excess water will spill out and be unavailable later in the summer when temperatures typically increase and precipitation decreases (CCSP 4.6, 2008).

In some cases changes to individual choices can be modeled using micro level data that allow the author to gain insights into individual preference and determine which factors drive a decision (Shaw and Loomis, 2008). Shaw (1996) uses microdata to analyze the impact of changes in lake levels on recreational use. In multiple studies, reduced water levels in reservoirs or lower in-stream flows have been shown to cause decreased recreational use (Shaw, 2005). Using similar microdata, Jakus et al. (1997) evaluate recreational fishing within reservoirs in the TVA region. Activities like boating that require a minimum water level are particularly susceptible to decreased water levels and stream flows. In addition, low water levels could leave infrastructure such as boat docks, ramps, and marinas unusable (CCSP 4.6, 2008).

Fishing also stands to be heavily affected by climate change given that water flows and temperature both play important roles in the health of the fish population. Pendleton and Mendelsohn (1998) use a random utility model to calculate the value of the effects of climate change on freshwater anglers in the northeastern United States. They find that fish populations will be altered, and thus angler utility will change. Coldwater fish populations such as trout may be diminished while warmwater populations may increase (see Chapter 6 for further discussion of this effect). The net impact of the changes of relative fish populations on anglers is dependent on the net fish population change and anglers' willingness to substitute between fish species. U.S. EPA (1995) predicts that warmer water temperatures could eliminate stream trout fishing in eight to ten states and that an additional eleven to sixteen states will lose half of their coldwater stream habitat. The Natural Resources Defense Council (NRDC, 2002) predicts that in Tennessee, 13-20 percent of suitable trout habitats will lose all trout by 2060 and 20-40 percent of streams will lose all trout by 2090. While the overall impacts on recreational fishing may be tempered by the ability to substitute for different species or water bodies, Ahn et al. (2000) calculate a two to twenty percent decrease in the utility derived from trout fishing depending on a projected temperature increase ranging from one to five degrees Celsius.

Changes to water resources, which diminish habitats or lead to species loss, will also affect the availability or quality of wildlife viewing (see Section 7.2.2.2 below for more information about effects on wildlife viewing; Wall, 1998; Kinnell et al., 2002).

7.2.2.2 Changes to Terrestrial Ecosystems

Various forms of terrestrial recreation (for example, hunting, hiking, camping, wildlife viewing) are also likely to be affected by climate change. Changes to wetland ecosystems caused by climate change will influence recreational opportunities such as wildlife viewing and waterfowl hunting. Pioani and Johnson's (1993) study on the effects of climate change on prairie wetlands indicates that there could be "a dramatic decline in the quality of habitat for breeding birds, particularly waterfowl." In addition to diminished habitat, the timing of bird migration patterns may change as well (Marra et al., 2005). As habitats and migratory patterns change, waterfowl hunters, wildlife viewers, and photographers that rely on these resources for recreation may not be able to see certain species or will have to shift their schedules and locations.

Iverson et al. (2007) modeled the response of 134 tree species in the eastern United States to climate change. Their model, which looks at potential suitable habitats for various species, found that under a high carbon trajectory, 66 species gain and 54 species lose at least 10 percent of their habitat. Joyce et al. (2001) expand on the issue of changing habitat ranges and composition by noting that this will have unknown impacts on wildlife and insect populations. According to the report, the effect on these populations will depend largely on their dispersal abilities and the interaction with new invasive species.

Sanders and Easley (2006) studied the effects of climate change on western national parks. According to the report, increased temperature and drier conditions may lead to increases in wildfires that disrupt summer use of the parks. In addition, the characteristic regional plants and animals are expected to change and in some cases be driven to extinction due to changing climates, habitats, and invasive species. All of these changes will have large effects on the recreational opportunities provided and therefore, impact the enjoyment of the area. MacMillan et al.'s (2001) study of woodland habitat shows that people value certain woodland habitats and specific species. The loss of these habitats or species therefore would diminish the enjoyment people receive from visiting the area.

7.2.3 Economic Effects and Modeling

In order to understand the effect of climate change on recreation, the following issues must be taken into account:

- Effects of climate change on recreational resources
- Effects of changes in these resources on recreational opportunities and user demand/enjoyment

- Availability of data and modeling frameworks to quantify the effects

While there are numerous studies on the effects of climate change or on the economic value of recreational opportunities, there are relatively few that attempt to link the two to quantify the effects of climate change on recreational opportunities (CCSP 4.6, 2008). The following section focuses on studies that attempt to do both by modeling changes in recreation due to climate change.

Among the recreation valuation models, the two dominant approaches for measuring use values are the Travel Cost Model (TCM) and the Random Utility Model (RUM). Both of these model frameworks are widely used in the recreation literature and can also be applied in conjunction with climate change studies. A detailed explanation of each of the models is beyond the scope of this report; for more information, the reader is referred to Parsons et al. (2003). At a fundamental level, the primary distinctions between the two models are that the TCM models measure value using willingness to pay and treat each amenity as a single good which is bundled together in a *single* purchase or choice, while the RUM models quantify preferences through visitation days and rely on an index of quality which is estimated by comparing alternative choices faced by a consumer over the course of a *season* or longer (Pendleton and Mendelsohn, 2000). Shaw and Loomis (2008) point out that the analytic limitations are not necessarily in creating the models themselves, but rather in acquiring the necessary data.

Below we discuss general studies of changes in visitation days due to climate change, followed by a number of studies looking at such changes within geographically specific regions.

7.2.3.1 Models Measuring Value Changes through Changes in Visitation Days

Loomis and Crespi (1999) and Mendelsohn and Markowski (1999) each model the effects on various recreation participation under an assumption of seven percent increase in precipitation and 2.5 and 5 degree Celsius temperature increases. Each study finds that small increases in temperature increase participation in water activities while snow sports lose participants. Loomis and Crespi (1999) base their study on visitation data from U.S. Army Corps of Engineers reservoirs. The data are regressed as visitation by recreation activity as a function of land area, water area, population, and monthly temperature and precipitation. The Mendelsohn and Markowski (1999) study regresses state level data on visitation by recreation activity as a function of land area, water area, population, and monthly temperature and precipitation data. To place a monetary value on the changes in recreational activities (visitor days) due to climate change, each study applied values derived from various economic valuation studies to their findings. Mendelsohn and Markowski (1999) find that warmer temperatures increase recreational benefits in the U.S. by up to $2.8 billion. If temperature increases five degrees Celsius, the net benefits increase to $25.9 billion. In each scenario, fishing, boating, and camping each reap sizable benefits while skiing and wildlife viewing are worse off. Loomis and Crespi (1999) reach a similar conclusion, finding that if use remains at 1990 levels, a 2.5 degree Celsius temperature increase would translate to a $2.75 billion net gain.

7.2.3.2 Models Measuring Value of Changes in Recreation for Specific Areas

According to CCSP, specific case valuation studies of climate change on recreation have been rare. As noted above, Pendleton and Mendelsohn (1998) examined sport fishing in the northeastern United States; Scott and Jones (2005) modeled changes in tourism in Banff National Park, Canada; Scott et al. (2007) studied changes in Waterton National Parks, Canada; and Loomis and Richardson (2006) reviewed changes to Rocky Mountain National Park. Of these studies, none is specifically relevant to the TVA service region.

7.3 Discussion

7.3.1 The Effect of Climate Change on Recreation in the Tennessee Valley

Several important points can be gleaned from the preceding literature review and characterization of TVA region recreational activities:

- Climate (temperature, precipitation) has been documented to be an important determinant of participation rates and patterns for a large class of recreational activities. Temperature in particular can have both positive (more participation) or negative (reductions in participation) effects, depending on the magnitude of the change and the given recreational activity.
- Current recreational activities are heavily dependent on the water resources of the region. Depending on the nature of the activity, changes in water resources have been documented to have both positive and negative effects on participation in other settings. This finding suggests that changes in water resources, such as changes in stream flows, reservoir water levels, and water temperatures due to climate change are likely to have a substantial effect on participation rates and ultimately on economic values associated with that participation, given the popularity of swimming, boating, and fishing within the region.
- An increasingly important recreational activity in the TVA region and nationally are non-consumptive uses of wildlife (viewing, photography) and other ecosystem-dependent activities. The IPCC has suggested that climate change will have effects on ecosystem outputs and service flows (Pioani and Johnson, 1993). For example, climate change is expected to adversely affect various species of birds, particularly those dependent on wetlands or riverine environments. If so, climate change could adversely affect these types of activity in the TVA region.
- Recreation frequently involves substitution between activities in the face of adverse weather or other external forces. Under climate change, it is expected that similar substitutions may occur. The net change in economic value to participants will depend on the quality and location of these substitute activities. If the suite of activities is reduced under climate change, then economic well-being may be adversely affected. For example, if all cold water fishing opportunities are eliminated in the TVA region by climate change, then participants must either travel north to seek similar activities or substitute into less desirable forms of recreation. In either case, their welfare is reduced.
- As noted above (see Loomis and Crespi, 1999), population is typically used as an explanatory variable for forecasting recreational demand. Climate is also known to affect

migration patterns between regions. To the extent that population may increase or decrease due to climate change within the TVA region, demand for recreation may change.

7.3.2 Data and Modeling Gaps and Recommendations for Future Research

The TVA region is characterized by a wide range of activities and a high level of recreational participation by its residents. The observations gleaned from this review can be instructive on potential affects on climate change on the region. However, the lack of studies specific to recreation under climate change, both in the region and more broadly, makes these estimates mostly of a qualitative nature. To fully understand the potential quantitative effects of climate change within the region, a systematic approach to measurement is needed. The most applicable framework or approach would be a RUM. Such models have been developed and applied in a wide range of settings, often encompassing a large geographical area (for example recreational fishing in Alaska). As Loomis and Crespi (1999) note, development of such models is straightforward; the challenge is in collecting or obtaining the necessary data. Although RUM models are data intensive and as a result may be costly to solve and implement, they can be quite helpful to deal with broad scale management of recreational resources. Even in the absence of climate change, such a model could prove useful in the management of TVA services by enhancing recreation use and associated economic welfare.

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8
POTENTIAL EFFECTS OF CLIMATE CHANGE ON AIR QUALITY

8.0 Introduction

Air quality generally refers to the amount of air pollutants in the air from different sources either emitted directly or formed in the atmosphere due to chemical reactions. The major pollutants of concern are ozone, fine particles ($PM_{2.5}$), mercury, lead, carbon monoxide, nitrogen dioxide, and sulfur dioxide. Most urban areas in the United States are in non-attainment of the National Ambient Air Quality Standards (NAAQS) for ozone and $PM_{2.5}$, and thus we have limited our review to those pollutants with one exception. Mercury is an air toxic that is of particular interest to EPA for its health effects and is also included in the review.

Like most places in the United States, air quality in the TVA region has improved over the years; however, air quality standards have also become stricter during that time. There are areas in Tennessee currently that do not meet one or both of the NAAQS for ozone and $PM_{2.5}$. Air pollution is highly sensitive to meteorological conditions, and hence any changes in future climate could affect future ozone and $PM_{2.5}$ concentrations. For example, changes in temperature affect chemical reaction rates in the atmosphere, thus affecting the secondary air pollutants like ozone and $PM_{2.5}$. Other climate variables that affect air quality include precipitation, cloudiness, wind speed, relative humidity, mixing depths, and frontal passages. The substantial uncertainty associated with how these variables might change with changes in climate, especially at the regional level, makes it difficult to make accurate predictions about climate change-induced changes in air quality. Climate also influences biogenic emissions due to the effects of temperature and solar radiation on biogenic volatile organic compounds as well as emissions from wildfires; these changes can consequently affect air quality too. This literature review examines various studies that describe future air quality in the 2050 timeframe. All of these studies rely on use of global circulation models as well as regional air quality models. The research has focused more on the climate impacts of ozone, but recent studies have also started examining effects on $PM_{2.5}$.

In general, the model results suggest that ozone will increase overall as a result of changes in climate; however, there are spatial variations when looking at different regions of the country and there is less agreement among models at regional scales. Models do not show a clear indication of direction of change for $PM_{2.5}$ as a result of changes in climate, with some showing increase in $PM_{2.5}$ and others showing a decrease. Changes in air quality associated with projected emissions changes over the next forty years are likely considerably greater than changes in air quality associated with changes in climate. Most studies look at the United States as a whole or report results for particular regions, with Tennessee combined with the southeast region. Therefore, the results presented in this chapter are mostly for the southeast and not specific to

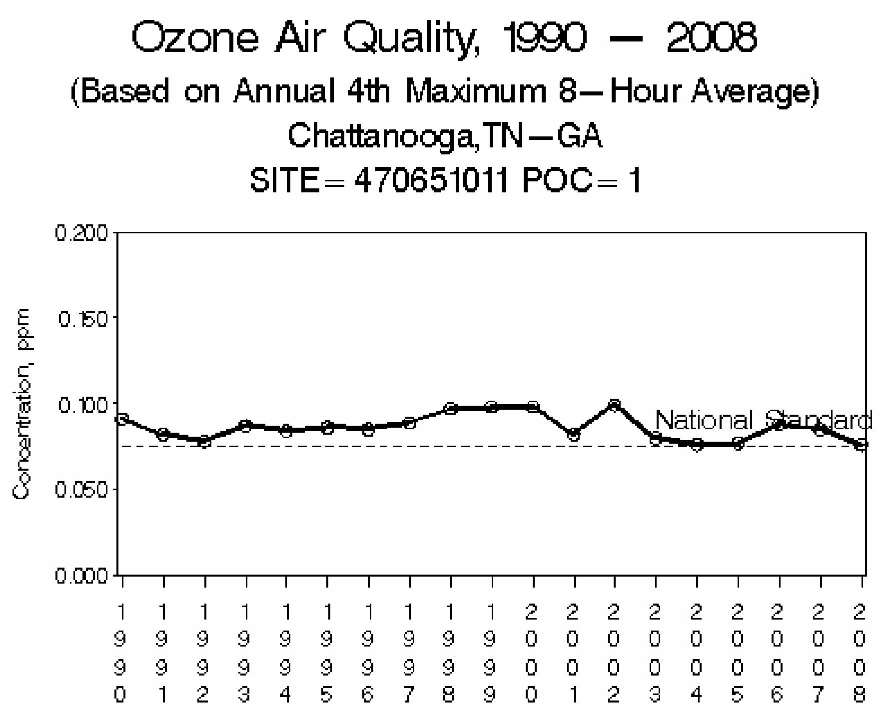
Tennessee. This chapter describes air quality in the Tennessee area in general, reviews literature on the potential effects of climate change on ozone, $PM_{2.5}$, and mercury and concludes with a discussion of the effects of climate change on air quality in the southeastern United States. To date there have been no modeling studies examining effects of climate change on mercury, so only a general discussion of that issue is included here.

8.1 Air Quality in the Tennessee Area

EPA is responsible for promulgating NAAQS for criteria pollutants including ozone and $PM_{2.5}$. In 2008, EPA revised the NAAQS for ground-level ozone from an 84 ppb (parts per billion) 8-hour average standard to a 75 ppb 8-hour average standard. In 2006, EPA also revised the NAAQS for daily $PM_{2.5}$ from 65 $\mu g/m^3$ to 35 $\mu g/m^3$, while maintaining the annual standard at 15 $\mu g/m^3$. While few areas were in non-attainment for the previous ozone and $PM_{2.5}$ standards, many more areas are expected to be in non-attainment with the promulgation of new standards.

Figures 8-1 and 8-2 illustrate ozone trends in four major cities in Tennessee, all of which are expected to be in non-attainment for the new ozone standard (indicated by the dotted line in Figures 8-1 and 8-2). As shown, ozone concentrations in these locations have dropped over the years, but are higher than the new standard of 75 ppb 8-hour average. Figure 8-3 (courtesy of Cassie Wylie, TVA) shows all of the counties in Tennessee and neighboring states that are expected to be in non-attainment for the new ozone standard. Most counties with urban areas are expected to be in non-attainment.

Figure 8-4 (courtesy of Cassie Wylie, TVA) shows all of the counties in Tennessee and neighboring states that are in non-attainment for the $PM_{2.5}$ standard promulgated in 2006. In Tennessee, the Knoxville area and the Chattanooga are expected to be in non-attainment for $PM_{2.5}$ standard.



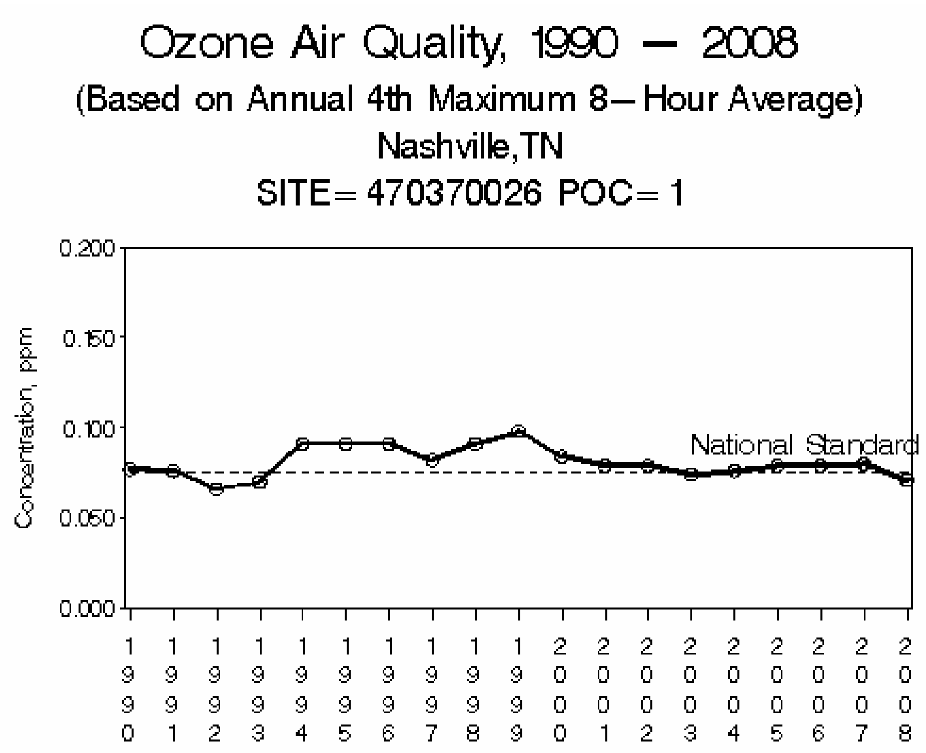
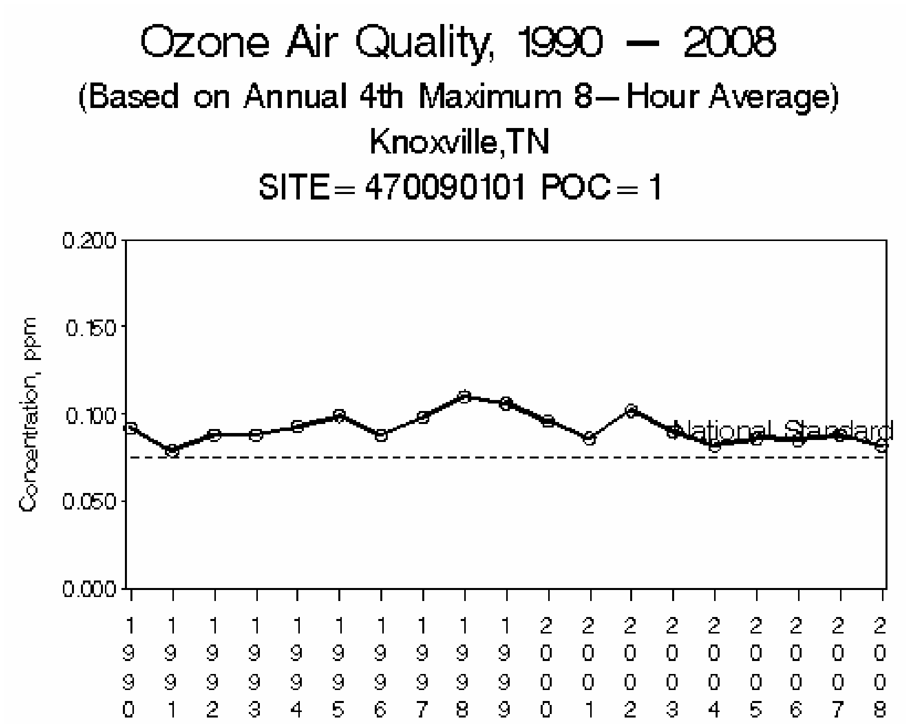


Figure 8-1
Ozone trends in Chattanooga (top) and Nashville (bottom)



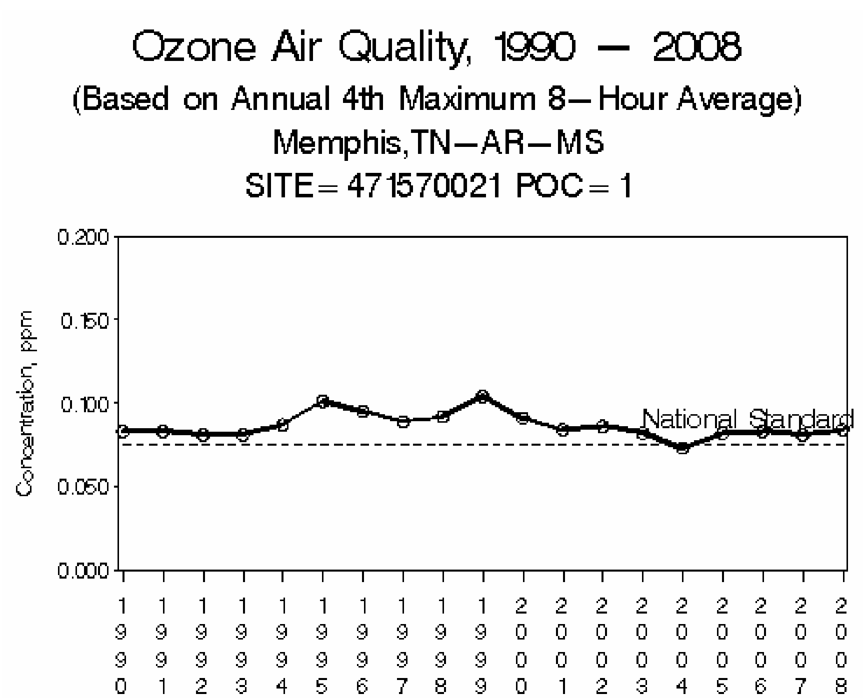


Figure 8-2
Ozone trends in Knoxville (top) and Memphis (bottom)

Source: EPA

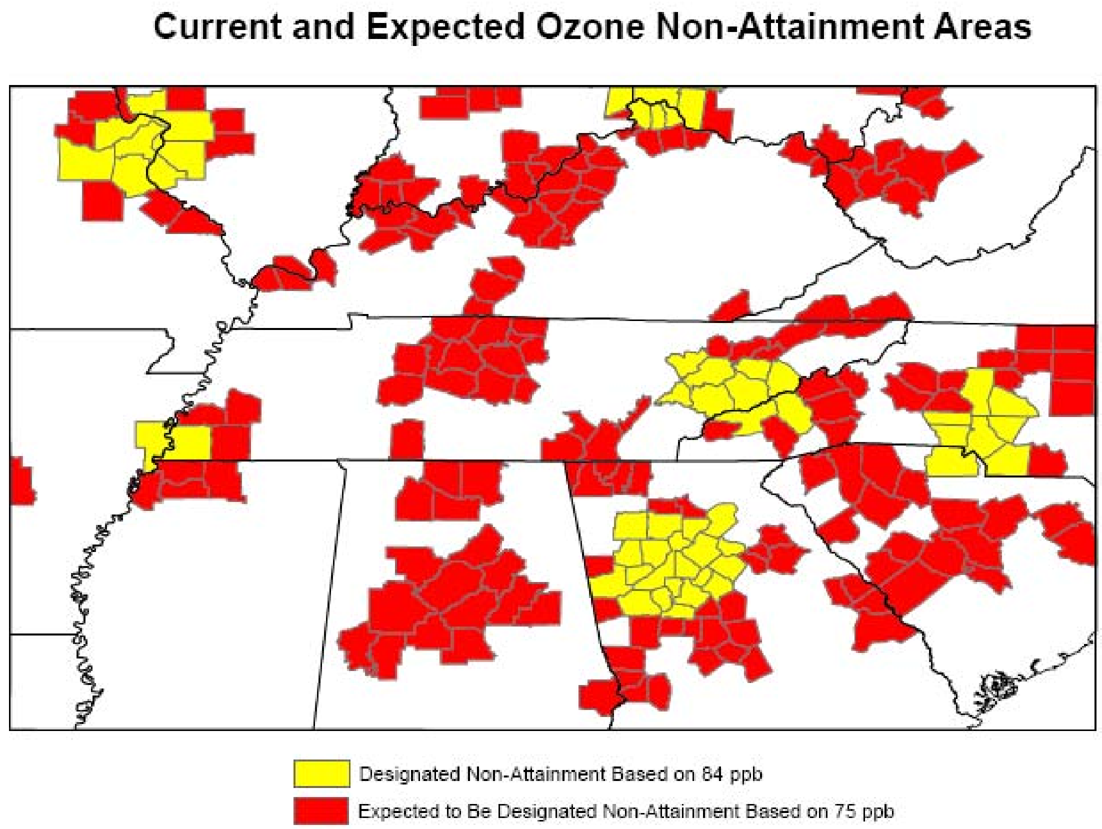


Figure 8-3
Probable ozone non-attainment counties based on 2005-2007 data

(Counties in yellow are currently in non-attainment; counties in red are expected to be in non-attainment under the new ozone standard).

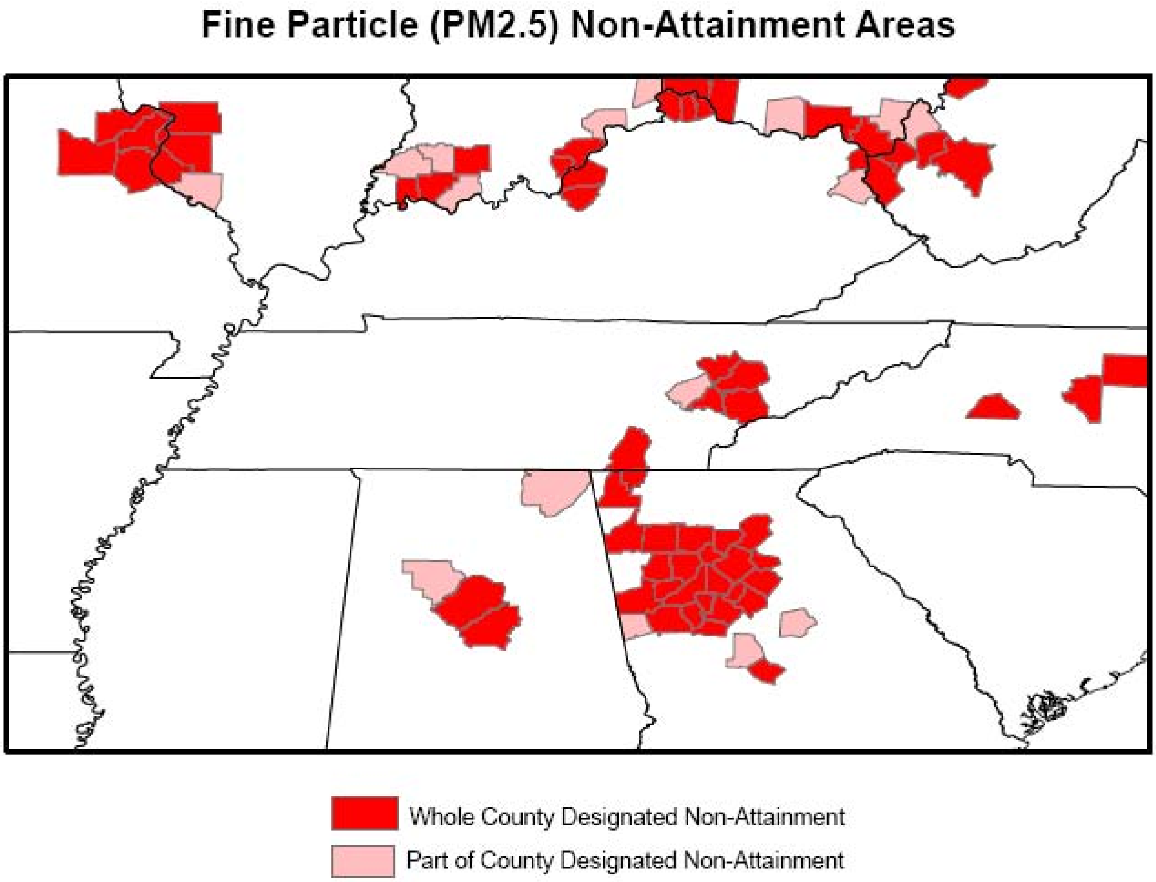


Figure 8-4
Probable $PM_{2.5}$ non-attainment counties in Tennessee and neighboring states based on 2005-2007 data

8.2 Literature Review

This section describes recent studies examining the effect of climate change on regional ozone, $PM_{2.5}$, and mercury in the United States with emphasis in the southeastern United States. As mentioned earlier, none of the studies that appear in the literature review describe the effect of climate change specifically in the Tennessee area, so for this review we will assume changes in the southeastern United States are an appropriate surrogate for changes in Tennessee. All studies rely on the use of different global circulation models (GCMs) in combination with chemical transport models (CTMs) to estimate the effect of climate change on air quality. The general approach is to run a GCM for a particular future IPCC scenario and use the output of the GCM to drive the CTM to simulate future ozone and PM concentrations. Sometimes a regional climate model (RCM) may be run using the boundary conditions provided by the GCM to get finer resolution meteorological variables for the CTM. Various modeling studies have been conducted recently that examine the air quality concentrations from 2050 to 2100 time frame with most of them focusing on 2050. For the purpose of inter-comparison, this review will focus only on studies that report results for 2050.

8.2.1 Effect of Climate Change on Ozone

Table 8-1 shows the various studies that have been included in this review to examine the effect of climate change on ozone. We focus on these studies because they are recent and because each investigates the air quality impacts for the 2050 climate. The first three studies assumed the A1B scenario for future (2050) climate while the last three studies assumed the A2 scenario. The A2 scenario is one of the more severe IPCC scenarios in terms of future population growth and temperature change. All the studies relied on the same general methodology: 1) run the air quality model with the present climate and present emissions; 2) run the air quality model with the future climate, present anthropogenic emissions, and biogenic emissions based on the future climate; and 3) use the difference in results from the two simulations as an indication of the effect of climate change alone. The first thing one can notice from Table 8-1 is that no two studies agree with each other, and some show results that are diametrically opposite to the others (even for the same climate scenario). The reason for this discrepancy is that the studies use different models and the modeling assumptions are quite different from one study to another. Although these reasons can partly explain the differences in results, it is nonetheless difficult to draw any robust conclusions about the effect of climate change on future ozone levels in various parts of the country with any degree of confidence.

Jacob and Winner (2009) have also summarized various studies that used GCMs and CTMs to examine the effect of climate change on ozone, although some of the more recent studies were not included because they were not published at the time of their review. Also, they include all studies, irrespective of which year was considered for future climate and whether the study was global or focused on the United States. They conclude that climate change will decrease the ozone background in the lower troposphere, mainly because of increases in water vapor concentrations in a warmer world. They also conclude that ozone concentrations will increase in the polluted regions (in general) as a result of climate change, although there are some regions that experience decreases in ozone. Jacob and Winner (2009) suggest that the major reason for discrepancies in results from different studies is the difference in meteorology among the various

GCMs/RCMs used for the studies. Other reasons could be differences in chemistry, deposition, and the treatment of natural emissions in the CTMs.

Table 8-1
Studies examining effect of climate change on maximum 8-hour ozone (percent) for the 2050 timeframe

IPCC Scenario	Models Used	Overall Effect in the U.S.	Effect in Southeastern U.S.	Reference
A1B	GISS GCM; MM5; CMAQ	-2.5 in Midwest; +2.8 in Northeast	Insignificant	Tagaris et al. (2007)
A1B	GISS GCM; MM5; CMAQ	+5 in Northeast, -3 in Midwest	+3 to +5	Nolte et al. (2008)
A1B	GISS GCM; GEOS-Chem	+2 in Northeast, +5 in Midwest	Insignificant	Wu et al. (2008)
A2	PCM; MM5; CMAQ	+5 in Northeast; -8 in Texas	-6	Avise et al. (2009)
A2	GISS GCM; MM5; PMCAMX	-2 in Northeast; +4 in Midwest and Texas	+7	Dawson et al. (2009)
A2	GISS GCM; MM5; PMCAMX	+7 in Northeast; +5 in Midwest and Texas	+2 to +7	Racherla et al. (2009)

It is instructive to evaluate the results from the studies shown in Table 8-1 separately for each scenario. For the A1B scenario, the three studies reviewed here agree that the ozone concentrations in the Northeast would increase due to climate change, although the extent of increase is different. The results differed for the Midwest among the three studies. Tagaris et al. (2007) and Nolte et al. (2008) predicted a decrease in ozone, whereas Wu et al. (2008) predicted an increase. Studies also disagreed for the effect in the southeastern United States. While Tagaris et al. (2007) and Wu et al. (2008) agreed that the effect of climate change on ozone in the Southeast was small to insignificant; Nolte et al. (2008) predicted a big increase in ozone. It is not possible to attribute the differences in results from these studies to any one factor because although some studies used the same models, they differed in many other respects. For example, the GEOS-Chem model used by Wu et al. (2008) has a very different isoprene mechanism than used in the CMAQ model in Tagaris et al. (2007) and Nolte et al. (2008). Wu et al. (2008) suggest that increases in isoprene emissions in the Southeast due to climate change actually tends to reduce ozone levels because of "(1) sequestration of NO_x as isoprene nitrates (Wu et al., 2007) and (2) direct ozonolysis of isoprene (Fiore et al., 2005)." This result is in contrast to the CMAQ model, which shows an increase in ozone in the southeast as a result of increase in isoprene emissions.

Differences in results from different studies are more contrasting for the A2 scenario than for the A1B scenario (Table 8-1). For example, Avise et al. (2009) and Dawson et al. (2009) give diametrically opposite results on the effect of climate change on ozone. This discrepancy could be mostly due to the fact that these studies use different GCM and CTM models. Dawson et al. (2009) and Racherla et al. (2009) use the same models and agree more or less with each other on the results except in the Northeast where the former shows a decrease and the latter shows an increase. The main difference between these two studies was that Racherla et al. (2009) assumed biogenic emissions in 2050 corresponded to 2050 climate for the entire world, whereas Dawson et al. (2009) assumed biogenic emissions in 2050 corresponded to the present level for the United States while they varied with climate for the rest of the world.

In some of the studies shown in Table 8-1, the investigators also examined the effect of changes in anthropogenic emissions on future air quality. For example, Tagaris et al. (2007) predicted a reduction in 8-hour maximum ozone of 28 percent in the Southeast due to a combined effect of emissions changes and climate change from 2000 to 2050, whereas the effect due to climate change alone was negligible (an increase of 0.3 percent). For the Northeast, the combined effect due to climate change and emissions reduction was a 20 percent reduction in 8-hour maximum ozone, while the effect due to climate change alone was an increase by 2.8 percent. Wu et al. (2008) also found large reductions (5 to 20 percent) in ozone from 2000 to 2050 due to changes in anthropogenic emissions alone. Avise et al. (2009), who modeled the A2 emissions scenario (in which the anthropogenic emissions increase from the present level), found that ozone concentrations increase by three to seven percent due to emissions changes alone. In general, the signal due to changes in emissions alone is predicted to be much larger and shows consistency across models for the same emissions scenario than the signal due to climate change.

Overall, modeling results describing the potential effect of climate change on ozone in the Southeast vary considerably, and one can not say with any degree of confidence how ozone might respond there to a changing climate. Most modeling studies do suggest an increase in ozone for the Northeast, although there are exceptions. Results for the Midwest also vary quite a bit from one study to another. The main reason the models are showing different results is that ozone concentrations depend on so many factors and the models do not agree with each other at the regional levels. For example, although the GCMs may generally predict a warming trend from present to 2050, they differ significantly from each other when it comes to trends in temperature at the regional level and they also differ significantly in their predictions of cloudiness, which affect ozone concentrations significantly. The CTMs used in these studies also differ in their treatment of atmospheric chemistry as well as the mechanisms used in projecting future biogenic emissions.

8.2.2 Effect of Climate Change on $PM_{2.5}$

Table 8-2 shows the various studies that have been included in this review to examine the effect of climate change on $PM_{2.5}$. We have followed the same principle in selecting the studies as was followed for ozone; in fact, three of the four studies selected are the same as shown in Figure 8-4, as they examined both ozone and $PM_{2.5}$ effects. According to Jacob and Winner (2009), the effect of climate change on PM is more complicated and uncertain than for the ozone because different PM components may respond differently to different meteorological variables and because of various compensating effects. In their review of effect of climate change on PM, Jacob and Winner (2009) state that there is little consistency between different studies including the sign of the effect. Thus, it may be said that the modeling studies to examine the effect of climate change on PM are less reliable than for ozone.

Table 8-2
Studies examining effect of climate change (percent) on $PM_{2.5}$ for the 2050 timeframe

IPCC Scenario	Models Used	Metric Used	Overall Effect in the U.S.	Effect in Southeastern U.S.	Reference
A1B	GISS GCM; MM5; CMAQ	Annual Mean	+4.2 in Midwest; +6.5 in Northeast	-2.4	Tagaris et al. (2007)
A1B	GISS GCM; GEOS-Chem	Annual Mean sulfate	+5 to +10 in Midwest and Northeast	-10	Pye et al. (2009)
A2	PCM; MM5; CMAQ	Annual Mean	+2 in Northeast; -10 in Midwest	-20	Avise et al. (2009)
A2	GISS GCM; MM5; PMCAMX	Monthly Mean	+5 in Northeast; -2 in Midwest in January +10 in Northeast; +20 in Midwest in Jul	-10 in January +40 in July	Dawson et al. (2009)

As can be seen from Table 8-2, results for the effect of climate change differ more for the $PM_{2.5}$ than they do for ozone. These differences could be due to the fact that $PM_{2.5}$ concentrations are more sensitive to precipitation and cloudiness—two variables that are highly uncertain in the GCMs and RCMs. One could also conclude that the modeling systems are not robust enough at this time to estimate the effect of climate change on $PM_{2.5}$ with any degree of confidence.

As with ozone, the effect of emissions changes is much more significant than the effect of climate change on $PM_{2.5}$ concentrations. For example, Tagaris et al. (2007) predicted a reduction of 31.4 percent in annual $PM_{2.5}$ concentrations in the Southeast due to combined effect of emissions changes and climate change from 2000 to 2050, but only a reduction of 2.4 percent due to climate change alone. Avise et al. (2009) predicted an increase of 35 percent in annual $PM_{2.5}$ concentrations in the Southeast due to emissions change from 2000 to 2050, but a reduction of 20 percent due to climate change.

8.2.3 Effect of Climate Change on Mercury

As mentioned earlier there have been no modeling studies to date examining effect of climate change on mercury, but there are many possible ways climate change can affect mercury cycling and there are few studies that have examined how mercury emissions from oceans and land reservoirs might change as a result of climate change. According to Selin et al. (2008), the amount of mercury stored in soils (1.2×10^6 Mg) is many times more than what is in the atmosphere (5×10^3 Mg) or oceans (4×10^4 Mg), so the soil mercury could be an important source in view of increased wildfires as a result of climate change. Turetsky et al. (2006) suggest that projected increases in boreal wildfire activity due to climate change will increase atmospheric mercury emissions. In addition to increased volatilization of mercury from ocean and land reservoirs, there may also be changes in anthropogenic emissions due to socioeconomic factors. Streets et al. (2009) estimate that the global mercury emissions could range from a reduction of 4 percent to an increase of 96 percent from 2006 to 2050 depending on which IPCC scenario is chosen. The biggest factor explaining increase in emissions from socioeconomic factors is the expansion of coal-fired electricity generation in the developing world, particularly Asia.

8.3 Summary and Future Needs

In summary, the literature review suggests that ozone should increase in general with climate change; however, at the regional level the effects can be positive or negative. For the southeastern United States, the results differ to a great extent between different studies, due perhaps to the way in which isoprene chemistry is treated in the air quality models. Isoprene emissions are expected to increase in the southeast due to temperature increases and, depending on how the isoprene chemistry is treated in the models, which may either lead to a decrease or an increase in ozone. For $PM_{2.5}$, the modeling results are too uncertain to draw any firm conclusions. Both for ozone and $PM_{2.5}$, the modeling studies predicted a bigger response due to projected emissions changes between 2000 and 2050 than due to climate change. There are no modeling studies available to date that estimate effect of climate change on mercury, but it is expected that there will be increased vitalization of mercury from oceans and soil stocks.

Since the modeling results were only available at the regional level, no information was specifically available for the TVA region. One could obtain the modeling results from the different groups involved in these studies and analyze the results specific for Tennessee and surrounding areas, but it is not clear whether that would lead to any definitive conclusions.

Another possibility is to conduct a comprehensive study to evaluate the effects of climate change on air quality, although such a study would require collaboration among various research groups. This study would involve running a suite of models with similarly controlled experiments so that a better understanding of the differences in results could be achieved. Because most current studies examining the effect of climate change on air quality in the United States rely only on couple of different GCMs and use different assumptions, it is difficult to make direct comparisons between them.

8.4 References

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9
SUMMARY AND SYNTHESIS OF RESULTS

9.0 Introduction

This chapter provides a summary and synthesis of results from the previous chapters and identifies the strongest conclusions across all sectors. We also make recommendations about where further research on impacts in the TVA region would be most useful. We first summarize and synthesize the key results, then provide a short list of options for further work.

9.1 Key results of this Assessment

The available literature on the impacts of climate change in the TVA region suggests the following conclusions:

1. **Water resources.** In this sector, the most important potential climate stressor for the region is precipitation—if precipitation declines, the region and in particular TVA operations could be significantly affected, because currently abundant water resources have resulted in the region's economy and recreation being very water-dependent. Temperature, however, also plays a role, in particular because the combination of temperature and precipitation affect soil moisture and runoff, and these factors are key determinants of agricultural water demand as well as water availability to support recreation and ecosystems. The available climate information suggests changes in runoff in the TVA region are likely to be modest, but some impacts could result from highly localized changes in the temporal distribution of precipitation. Multi-model means of climate results suggest that effects on most existing human uses of water (for example, for cooling water or hydropower) are also likely to be modest and occur within the range of existing adaptive capacity, although some adjustments in water planning will likely be necessary. The key effects of localized changes in water resources could be on ecosystem integrity. One major uncertainty is the future demand for water from agriculture sources. If currently rain fed agriculture requires irrigation, accelerating the already observed trend toward greater irrigation water demand for crops, the impacts of climate change in this sector could be substantial.
2. **Agriculture.** Agriculture is a significant and important component of the economy of the TVA region. National-scale analyses suggest the TVA region lies on the border of areas where agricultural productivity is likely to benefit from climate change (farther to the north) and the area where productivity is likely to suffer ill effects (to the south). As a result, within the TVA region the overall effects of climate on agriculture may be modest, but there are likely to be highly localized occurrences of "winners" and "losers" in this sector. The greatest uncertainty in estimating climate impacts relates to the high variation in forecasts of precipitation and water availability. Precipitation effects could be particularly important in the TVA region because the vast majority of crops are currently rain fed.

3. **Forest lands.** Forest lands are also economically important to the TVA region. Climate change is likely to lead to continued increases in forest productivity for the next 10-30 years, with higher temperatures and greater availability of carbon dioxide to support growth. Localized shifts in species distribution are nonetheless possible during this period. Some significant drying of soils is possible in Western Tennessee by 2030, and this risk increases after 2030. After the mid-century period, more pronounced forest species changes could be seen, which could require adaptive management to facilitate a change from a predominately hardwood to a predominately softwood forest. It is not currently clear whether this transition would result in losses to commercial timber operations, or whether the changes could be effectively managed through existing adaptive capacity in the commercial forest sector. As for water resources and agriculture, the greatest uncertainty in these results derives from uncertainty about future precipitation patterns.
4. **Ecological resources.** There is not much literature describing the impacts of climate change on ecological resources that is specific to the TVA region, but it is clear that the region is currently one of the richest in the nation in terms of biological diversity. In particular, the TVA region provides habitat to an unusually high concentration of threatened and endangered plant, wildlife, and aquatic species. Some of the more subtle changes in forest ecosystems that might present modest challenges to commercial forestry could have more substantial effects to currently threatened or endangered wildlife and plant habitats, but the lack of existing studies of these effects makes it difficult to be specific about which regions and species might be most threatened. Among aquatic species, temperature effects and changes in frequency, severity, and timing of extreme water flow events (both floods and droughts) could have substantial impacts, but as noted above the uncertainty in future precipitation patterns makes it difficult to forecast these events.
5. **Recreation.** The key finding in this area is that water-based recreation is a major activity in the region, so changes in water availability to support recreation are the key potential stressor. In response to any future substantial changes in water availability, we would anticipate substitution among recreational activities; however, it is not clear whether the range of recreational alternatives might be limited by climate change. As in any region, any conclusions about the quality of natural resources to support outdoor recreational opportunities need to be tempered by uncertainty in future demand for these activities, though it is probably reasonable to expect that demand for biking, hiking, hunting, fishing, and boating opportunities will remain strong in the TVA region.
6. **Air Quality**. The TVA region faces current challenges in maintaining air quality related to ozone and particulate matter, but air toxics are also a significant issue, and regional haze (closely linked to particulate matter) affects visibility in the region. Climate change affects each of these pollutants, but in different ways. Temperature has both a direct and indirect effect on ozone formation, the latter due to the effect of temperature on the emissions of volatile organic compounds, an ozone precursor that is released from both anthropogenic and biogenic sources. With temperatures projected to increase, ozone concentrations can be expected to increase, but there are many uncertainties in other meteorological variables that affect ozone. Another key uncertainty involves the atmospheric chemistry of isoprene, which would be released in greater quantities at higher temperatures, but could increase or decrease ozone concentrations. Particulate matter concentrations could be affected by soil drying, which would both increase the risk of wildfires and allow soil particles to become airborne

more readily. Increases in wildfires could also lead to increased releases of mercury to the air.

A common factor in virtually all of the key results of our review is the importance of water resources and water availability in the TVA region. In particular, water and uncertainty concerning future water availability is important not just for the major water users in the region (for example, hydro- and fossil electric power generation), but as a key input to agriculture, forestry, recreation, ecosystems (particularly potentially endangered species), and some aspects of air quality, that is, virtually every other affected natural resource in the region. Water is a critical resource in other regions of the country, but the TVA region may be especially vulnerable to climate change impacts on water availability because both human natural systems have been established based on the abundance of water resources (Karl et al. 2009).

Available information on the future profile of water availability is not sufficient to draw definitive conclusions, but further analysis might fill at least some of these critical gaps. Preliminary analysis of IPCC-sponsored climate model results for the region suggest that precipitation could decline in some areas, but risks of prolonged periods of reduced runoff (runoff is a measure that combines the effect of precipitation and temperature) are not likely to increase the TVA watershed.[19] Nonetheless, the spatial and temporal pattern of water availability could change significantly, which at a minimum would require adaptive changes in the operation of water supply infrastructure but could also require substantial infrastructure enhancements for storage and distribution systems, particularly in instances where climate changes move the timing of water demand and supply out of synch. The adaptive capacity of ecological resources in the face of these climate risks, however, may be more difficult to enhance, suggesting that at least some currently endangered species could be lost (Karl et al., 2009).

A second common factor in our results is that near-term effects that might be realized by 2020 are likely to be modest and within the range of existing adaptive capacity, and that effects will likely accelerate by 2050 and in some cases may exceed existing adaptive capacity. Drawing conclusions for the end of the century period is very difficult, owing to uncertainties in forecasting climate as well as forecasting the human and natural resource context in which impacts will be experienced. One possible exception is in the area of ecological resources, where the current endangered status of several species, as well as the high number of endemic species, likely makes them vulnerable to even the relatively modest changes in climate that could manifest by 2020.

9.2 Recommendations for Further Analysis

This literature review represents an important first step in understanding the impact of climate change in the TVA region. Our results are necessarily limited because, in many cases, the available literature does not include assessment of climate stressors and receptors specific to the TVA region. Further insights could be gained through region-specific modeling of impacts.

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[19] The preliminary analysis referred to here is work underway by authors Strzepek, Neumann, and Boehlert to evaluate changes in drought risk across the United States. The work was sponsored by EPA and is expected to be completed in late 2009.

We recommend that further work in the TVA region concentrate on modeling of the water resource sector as the central focus, with estimation of other impacts to be linked to a water sector model. Figure 9-1 provides a schematic of the flow of analyses we suggest. First, we suggest that further effort be devoted to characterizing the climate stressor data at a regional level, with focus on the temporal and spatial distribution of precipitation forecasts, but with consideration at the same time of temperature forecasts – as stated in Chapter 2, precipitation and temperature are closely linked both within the climate models and as factors influencing key physical impacts, such as runoff and soil moisture. Second, we suggest conducting an analysis of the possible range of future agricultural water demand—one of the key conclusions of our literature review is that, although current demand for irrigation water in the TVA region is modest, future needs might be much different as the timing of precipitation is altered relative to key growth periods for agricultural crops.

Third, we recommend that a water use model for the region be deployed using the full range of integrated climate stressor and agricultural demand forecasts, with detailed consideration of the operation of water storage facilities and key water uses. The goal would be to assess whether the existing water storage and distribution infrastructure includes sufficient adaptive capacity to support anticipated human uses of water, and after doing so whether sufficient water remains to support ecological requirements. Such an analysis could yield important insights into the potential for future water use conflicts in the region. Fourth, we suggest that several reduced-form impacts modules be developed that use as inputs the results of the prior three steps. While prior work suggests that complete analyses of the impacts in the agriculture, forest resources, ecosystems, and recreation sectors could be complex and resource-intensive, the literature review provides reference to a body of existing work that could be used to generate initial estimates of the physical and economic impacts in these sectors.

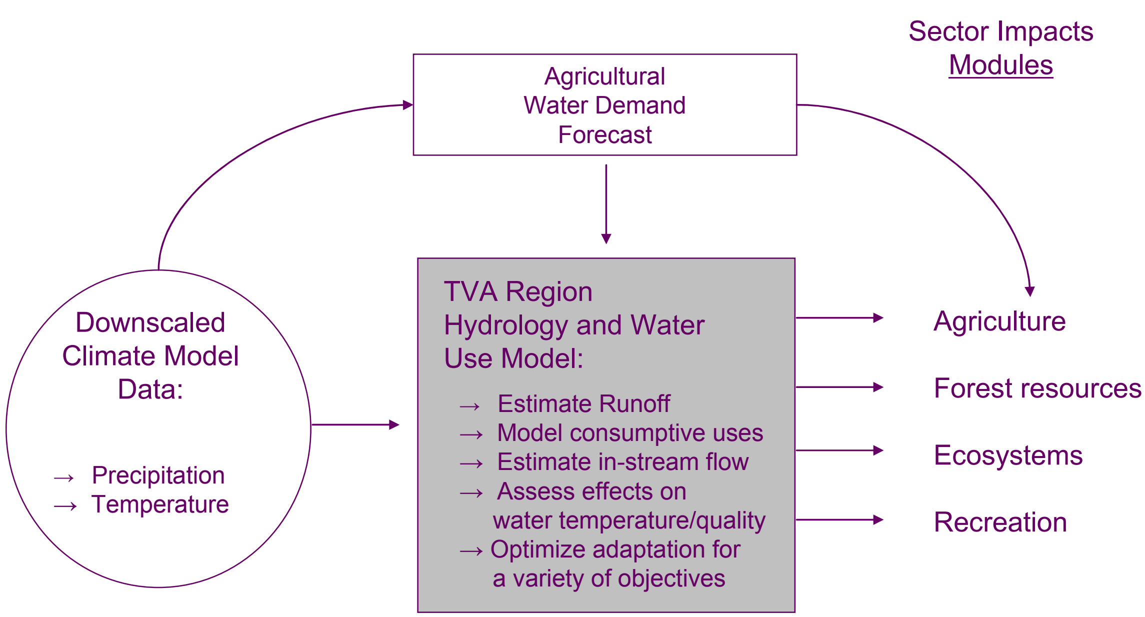

Figure 9-1
Schematic diagram of potential TVA region impacts modeling framework

A final insight from our research is that there is an enormous amount of ongoing and planned research to better understand the impacts of climate changes and develop robust plans for adapting to those impacts. In addition, there are numerous efforts to coordinate adaptation planning across multiple levels of government and within the private sector to share lessons learned from efforts already underway, to coordinate adaptation efforts with initiatives to reduce greenhouse gas emissions, and to clarify the type of climate science information necessary to effectively adapt to impacts. We encourage TVA to continue to monitor this research for new insights on the impacts of climate change and to play an active role in improving the adaptive capacity of the region.

9.3 References for Synthesis Chapter

Karl, Thomas R., Jerry M. Melillo, and Thomas C. Peterson, (eds.). 2009. *Global Climate Change Impacts in the United States*, Cambridge University Press.

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